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Dike Emplacement and Deformation in the Donner Summit Pluton, Central Sierra Nevada, California

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This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Geological Engineering.

by

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ACKNOWLEDGEMENTS

<Whew> I bet some of you out there figured I would never get done. But here I am with a completed M.S. thesis in geological engineering. I am not even sure where to begin and who to thank first, because each and every one of the following people have contributed so much to my life and my thesis. My mom and dad and Erika and Christy have always been supportive about my schoolwork. Without them close by in Sacramento with a guest room I would have gone crazy. I love them more than they can ever imagine. And no one will ever find a better field assistant than my sister Erika. Christina and Robert – What an incredible pair! Always had an extra room for me too, even in Florida. My grandma, who put up with me no matter what my mood. I love you. My e-mail account was priceless. The constant cheer and love I received from Becky, Kevin, and Erika helped me through many stressful times. The other graduate students who enjoyed the M.S. thesis ride with me, I salute each and every one of you. Especially Paul and Li (the two hardest workers in the department). Reno Mountain Sports, the entire crew, have been my constant sanctuary always making me take time out to smell the roses, or ski the powder.....And the Nevada Bureau of Mines group; Lindsey, Gary, Jim, and Dahpne; were wonderful to me too. Rich, I have learned more in two years than I ever expected. You have been a constant friend, confidant and support group. I really plunged into geological engineering (fracture mechanics) without a clue, and I couldn't have gotten to this point without you.

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ABSTRACT

Late-stage magmatic activity in the Mesozoic Donner Summit pluton has produced several generations of well-exposed igneous dikes. The emplacement and deformation of the dikes occurred while the pluton was still partially molten.

Dilation and shear displacement of the dikes and the geometry of the dikes in the field yield information about the mechanism and models resposible for dike emplacement and deformation. Mafic enclaves, which are consistently cross-cut by dikes, suggest that a slip patch mechanism can explain localized shear offset along dikes. Inelastic zones of deformation at the dike tip, where dike-parallel fractures form, indicate that some dikes created their own fractures as they grew and propagated through the pluton. Measurements of dike tip profiles show that a Dugdale-Barenblatt model of fracture mechanics is applicable to dikes and fractures, because the granite behaved inelastically independent of temperature and pressure.

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"As we crossed the state line under a clear sky and ascended toward Truckee, we passed big masses of competent, blocky, beautiful rocks bright in their quartzes and feldspars and peppered with shining black mica. The ebullient Deffeyes said, 'Come into the Sierra and commune with the granite.'"

Kenneth Deffeyes and John McPhee (1992)

INTRODUCTION

Dikes in granite are an important and fundemental mechanism of magma transport within the crust. There has been extensive work on the chemical and isotopic origin of the magma transported through the upper crust in dikes (Pitcher et al., 1985; Petford et al., 1993; Hibbard, 1980; Hibbard and Watters, 1985). This magma transport is diagnostic of volcanic and plutonic settings including the Sierra Nevada. In addition, numerous investigations of the kinematics have helped to clarify mechanisms of dike growth and propagation. Turcotte (1982) provides a clear review of the theoretical basis for transport of material in dikes. This previous research provides a firm foundation for studies of dikes, but there remain many aspects of dike emplacement and deformation which are important and can be addressed.

This study concentrates on the dike mechanics and deformational history in a particular pluton in the north central part of the Sierra Nevada batholith. A dike in this thesis is defined as a tabular body of igneous rock which crosscuts a rock mass. The igneous material in these dikes fills a dilated fracture plane. Although the dikes in the field area have been subject to both dilation and shear, these are not referred to as faults. A fault would normally imply that there has been displacement of the fracture walls relative to one another parallel to the fracture along the entire length (Pollard and Aydin,

1988) The dikes in the Mesozoic Donner Summit pluton, which is the study area for this thesis, show lateral displacement only along certain segments of the dike's total length. The sequence of deformation in the Donner Summit pluton preceded as generally shown in Figure 1 below.

Sequence of Deformation in the Donner Summit Pluton

OLDEST

Donner Summit pluton emplacement
  Enclave formation
  Dike intrusion/deformation
Pluton cooling and solidification

Hydrothermally-altered joints
High angle joints
Exfoliation Fractures
Blast Fractures

YOUNGEST

Figure 1. This figure summarizes the deformation that has occurred in the Donner Summit pluton from emplacement to present time. Deformation processes of associated structures prior to mafic enclave formation and dispersal were not considered.

The sequence of deformation is described in detail in the thesis. This study concentrated on the intrusion and deformation of dikes into the pluton. Late-stage magmatic activity in the Donner Summit pluton has produced several generations of well-exposed igneous dikes. They record a complex deformation sequence including dilation, and shear in any of three dimensions. The shear offset is apparent strike-slip, normal, and/or reverse movement relative to the sub horizontal, planar surface of the outcrops. Mafic enclaves, which predate dike intrusion, are cross-cut by dikes and are used as passive markers to show the dilation and shear along the dikes. In addition to cross-cutting other structures, dikes also cross-cut each other in a complicated sequence, indicating there has been more than one episode of dike emplacement in the pluton. After the pluton was fully solidified, other fractures formed in the pluton, some of which were hydrothermally-altered, while others were high-angle fractures with no alteration. The most recent developments are the formation of exfoliation fractures and blast fractures, respectively.

Purpose

This research focuses on several problems concerning the emplacement and deformation of the felsic dikes present in the Donner Summit pluton. The field area is shown in Figure 2. Initially this study began as a more comprehensive mechanics and kinematics study of dike emplacement in the Donner Summit pluton. As the questions began to multiply regarding the structural features in the field, it became desirable to focus the thesis to the main points below:

• ***Shear Displacement Along the Dikes.*** Several generations of dikes are recorded in the field. Along these dike planes, mafic enclaves are offset indicating apparent shear displacement along only portions of a dike. What is the deformation mechanism and its significance for the shear offset observed and measured in the field?

• ***Models of Pluton Emplacement.*** The dikes throughout the pluton do not appear to have a consistent orientation or cross-cutting sequence, but instead vary from outcrop to outcrop. By determining the relative orientation of the dikes to the pluton margin it is possible to test models of pluton emplacement, such as diapirism, ballooning, and dike propagation. Natural structural patterns in the pluton can be assessed using criteria proposed by Whitney (cooling, 1975), Bateman (dike emplacement, 1984), and Castro (ballooning, 1987) to assess the ascent and emplacement mechanism of the Donner Summit pluton.

• ***Passive or Forceful Dike Injection?*** Several models have been proposed to explain the injection of dikes into plutons. The new petrographic work and field observations

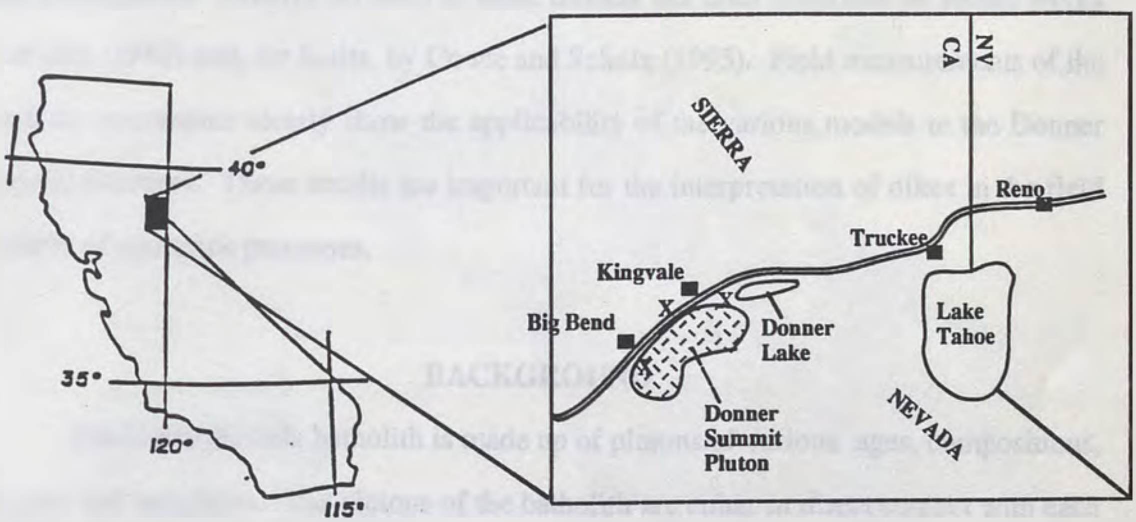


Figure 2. Donner Summit area in the Sierra Nevada, California. The selected sites for observations and measurements are marked with an "X".

reported in this thesis have determined whether the magma-filled fractures in the Donner Summit pluton were passively or forcefully intruded. Passive injection would indicate that dike material had intruded into pre-existing fractures, possibly formed from cooling or emplacement of the pluton. Forceful intrusion occurs when a fracture front grows and propagates as a result of magma pressure, often referred to as hydrofractures. These two proposals for dike injection have been studied and assessed in the Donner Summit pluton.

• ***Applicability of LEFM to Dikes*** . Dikes represent fracture of rock at relatively high confining pressure and temperature. Linear elastic fracture mechanics (LEFM) and other models, such as those of Dugdale (1960) and Barenblatt (1962), have been applied to dike propagation. Criteria for each of these models has been proposed by recent works by Rubin (1993) and, for faults, by Cowie and Scholz (1993). Field measurements of the crack tip geometries clearly show the applicability of the various models to the Donner Summit fractures. These results are important for the interpretation of dikes in the field in terms of causative processes.

BACKGROUND

The Sierra Nevada batholith is made up of plutons of various ages, compositions, textures and structures. The plutons of the batholith are either in direct contact with each other, or are found separated by septa of earlier emplaced rocks that were present before pluton intrusion (Chen and Moore, 1982; Bateman and Wahrhaftig, 1966). The Sierra Nevada batholith is composed of granitic rocks primarily of Mesozoic age. Figure 3 adapted from Bateman (1981) shows the geology and extent of the Sierra Nevada batholith and its surrounding country rocks. The Mesozoic Period in the Sierra Nevada was characterized by the formation of a synclinorium caused by the down-warping of Paleozoic rocks, and intrusion of plutonic masses into Paleozoic and early Mesozoic strata (Schweickert, 1981). Oblique plate convergence and subduction were occurring to

Figure 3. General geologic map of the Sierra Nevada and adjacent areas in east-central California. The Sierra Nevada batholith is shown along with country rocks. This figure was adapted from Bateman (1981; Fig. 4-1).

the west as the batholith was emplaced (Schweikert, 1981; Dickinson, 1981). Extensive regional shearing and tectonism has been reported for times before, during, and perhaps after pluton emplacement (Schweickert and Lahren, 1990; Saleeby, 1990; Paterson et al., 1991). These plutons as a result may contain a record of both syn- and post-emplacement deformation. Evidence of this deformation can be expressed as extensive joint or fault networks, foliation formation, and dike injection. The Donner Summit pluton has not been intensely affected by the regional deformation occurring at the time, and neither have the adjacent wall rocks. In contrast to this pluton, the southern Sierra Nevada batholith plutons have been subject to deformation as discussed later in the thesis.

The Donner Summit pluton composes part of the youngest plutonic sequence of the Sierra Nevada batholith which range in isotopic ages of approximately 88-125 Ma (Bateman, 1981). The pluton is located in the northeastern region of the Sierra Nevada batholith and has a biotite K/Ar age of approximately 97 Ma (Everden and Kistler, 1970). The early Cenozoic was a period of relative stability, until the Sierra Nevada range was apparently uplifted and tilted westward in the late Cenozoic (Bateman and Wahrhaftig, 1966; Unruh, 1991).

PREVIOUS WORK ON DIKES

Dikes have been observed and studied extensively around the world (e.g. Rubin, 1990; Castro, 1987; Prestvik et al., 1992). Dikes within individual plutons of the Sierra Nevada have been reported from various localities in the Sierra Nevada batholith (Pabst, 1928; Reid et al., 1983; Reid and Hamilton, 1987, Frost and Mahood, 1987; Hibbard and Watters, 1985; Furman and Spera, 1985). A variety of approaches have been used in studying dikes such as chemical/petrological research, field observations, and theoretical studies. The approach taken in this thesis combines aspects of theoretical fracture mechanics, field observations and petrographic research.

Chemical and Petrologic Research

Much work has been done on the petrologic and chemical features associated with dikes. Hibbard and Watters (1985) completed field work and petrologic studies which showed features in dikes of the Donner Summit pluton indicating a genetic relation to the host rock. In addition, they inferred that fracturing had occurred prior to complete crystallization of the host rock. Mixing and co-mingling processes in the pluton can also be assessed using petrologic work and chemical studies (Hibbard, 1980, 1981). Hibbard's paper (1980) also used petrologic studies to conclude that dikes in the Donner Summit pluton are formed by fluid injection into fractures and not by replacement or seepage along rock surfaces.

Reid and Hamilton (1987) report the occurrence of composite dikes, which consist of an outer phase of felsic pegmatitic material along with an inner phase of more mafic material, from a pluton to the south of the Donner Summit pluton. They have inferred that the outer pegmatitic part of the composite dikes reflect fracturing through a hot pluton, whereas injection of the more mafic dike material into the previously-formed pegmatite dikes occurred later under cooler conditions. Composite dikes are also found in the Donner Summit pluton, but no extensive work was done to compare Reid and Hamilton's observations in their field area to the composite dikes found in the Donner Summit pluton.

Field Observations

Numerous field studies of dikes have been undertaken in the Sierra Nevada batholith plutons. For example the growth of dilatant fracture (joint) networks in the Mt. Abbot quadrangle, located far south of this study area, was studied and reported in pioneering papers by Segall and Pollard (1983a,b) and Segall (1984). Strike-slip faults nucleated on previously-formed joints to produce complex arrays of faulted joints and splay cracks (Segall and Pollard, 1980, 1983; Martel et al., 1988; Martel and Pollard, 1989). Lockwood and Moore (1979) documented several sets of small strike-slip faults that appear similar in origin to those studied by Segall and Martel. The dikes in the Donner Summit area differ fundamentally from the crack and fault arrays studied by Segall and Martel and coworkers. These differences are addressed at the end of the thesis.

The geometry and characteristics of dikes measured in field studies have also been used to develop models of pluton emplacement. Transport of igneous material in fractures within the pluton has been suggested by Shaw (1980), Hibbard and Watters (1985), and Sparks and Marshall (1986). Frost and Mahood (1987) imply that dikes in the pluton they studied originated near the pluton's center and propagated outward toward its cooler margins. In this case, the direction of dike growth and that of magmatic fluid migration are generally the same (i.e., both outward toward the pluton margins). In contrast, Hibbard and Watters (1985) followed Whitney (1975) in suggesting that the fracturing related to dike injection in the Donner Summit pluton began in the cooler outer margins of the pluton and propagated inward. In this scenario, a two-stage evolution of the dikes is required because the fractures must first propagate inward, following the isotherms in a fashion analogous to columnar jointing of cooling lava flows (DeGraff and

Aydin, 1987), then tap some source of mafic magma and fill progressively back toward the outer margins of the pluton.

Theoretical Models Applied to Field Studies

Much is known about the mechanics of dikes injected at shallow depths, as summarized for example by Delaney et al. (1986), Rubin and Pollard (1987), and Rubin (1990) with their work on dikes in sedimentary and crystalline rocks. Pollard (1979), Rubin and Pollard (1987), and Rubin (1990) examined factors that could influence lateral propagation of a dike. Examples of these factors include inhomogeneous stress fields due to nearby dikes and changes in magma viscosity, and variations in the internal pressure of the dike filling material, which influences driving stresses and stress concentrations near the dike terminations (Pollard and Segall, 1987). Cowie and Scholz (1993) have recently published a plane strain model to explain the inelastic deformation that occurs during fault growth. They found that the fault tip displacement profile for an ideal, elastic mode II crack and the ratio of maximum displacement to the fault length are two factors that reveal information about the shear strength of the rock mass and the remote stress acting upon the during formation. Rubin (1993) examined the details of rock fracture processes in relation to crack growth and propagation. Rubin found factors most important to inelastic deformation of the dike plane would be dike tip suction (i.e. tapered profile), pore pressure, and remote stress. Both Cowie and Scholz's and Rubin's proposed models are discussed later in relation to the dike injection in the Donner Summit pluton.

P-T Conditions Accompanying Dike Emplacement

Dike emplacement in the study area is thought to have occurred at relatively high temperatures when the pluton was still partially molten (Hibbard and Watters, 1985; Reid and Hamilton, 1987) because the dike walls show interlocking grain textures and cracking through the grains is not observed. Transgranular cracking is normally associated with fracture growth through granular materials having strong cement or bonding between the grains. Fracturing of granite can occur at relatively high temperatures of 600°–800°C (Johnson et al., 1987) for a granitic pluton containing as much as 30–35 volume % melt (van der Molen and Paterson, 1979; Arzi, 1978). Hibbard and Watters (1985) propose that the fractures they observed in Donner Summit pluton have been emplaced in a hot (600°–800°C) granitic pluton containing as much as 30–35 volume % melt.

Van der Molen and Paterson (1979), in an experimental study of partially melted granites, found that nearly hydrostatic stress (all-around compression) promoted melt migration into fracture zones within rock which lacked a strongly preferred orientation (i.e. foliation). In contrast to this result they found that the application of differential stress produced fracture zones characterized by either dilation or shear displacements. Their experiments support the theoretical studies and field observations by requiring differential stresses for dike emplacement.

CRITERIA FOR SELECTED SITES

This study focuses on a well-exposed granodiorite pluton which has not been previously named (although borders of Cretaceous granite bodies nearby are shown on the new Chico map sheet being prepared by California Division of Mines and Geology [J. Doebrich, USGS-Reno, personal communication, 1992]). The pluton is herein termed the "Donner Summit pluton." The pluton has been mapped systematically on a 1:48,000 scale by Harwood (personal communication., 1993) and additional field mapping has been done during this thesis (see Fig. 2).

The Donner Summit pluton is located at an elevation of approximately 1951 meters (6400 feet) (Donner Pass 15 minute quadrangle, U.S. Geological Survey, 1955). Several outcrops have been selected due to their easy accessibility and abundant exposures of dikes and mafic inclusions. Because each of these sites has well-exposed felsic dikes, and examples of cross-cutting relations between the dikes and the mafic inclusions, it is possible to document structural relationships and field test theories of dike emplacement and deformation.

Three Key Research Sites

The study area is composed of three key sites located in the northern Sierra Nevada of California adjacent to Donner Lake and Truckee, California (see Fig. 2). The road log listed in Appendix A of this thesis provides detailed directions from Reno, Nevada, to each of these three sites.

One of the selected sites for detailed study is located at the west end of Donner Lake, where the granodiorite rises 372 meters (1220 feet) from the lake level. This is the observation point (Site One) for Donner Lake. At this local abundant dike cross-cutting relationships are obvious, as well as a large concentration of mafic enclaves. Models suggested by Delaney et al. (1986) and Rubin (1993) regarding dike tip geometries can be assessed at this selected site. A few hundred feet down from this observation point an outcrop also shows crosscut mafic enclaves and shear displacement along the dike plane (see Fig. 15).

The other two sites are just northwest of the Kingvale exit off Interstate 80 in California. Exposures of interaction between mafic enclaves and dikes are found in abundance between a Donner Summit Pass Road at the south fork of the Yuba River and

Interstate 80 at site two, Kingvale. Much of the previous dike work done by Hibbard and Watters (1985) was at this outcrop. Further west from this area at Kingvale is the third area, Rainbow Road/Big Bend. Fresh, blasted roadcuts across from Rainbow Lodge show enclave geometry and dike orientations in three-dimensions. The measurements used for stereoplots, dike dilation plots and displacement graphs have been collected from all three of these sites.

Measurement Technique

Several types of measurements were taken during the course of this thesis. The accuracy of these measurements is well controlled within a margin of error. The margin of error specifically refers to measurements of the felsic dikes. The characteristics of the dikes, i.e. width, were within approximately a grain diameter (± 2mm). The orientation, i.e. strike and dip, were within ± 5°. This section will describe in detail what type of measurements were taken and the procedure for collecting them. Appendix B shows common features measured and recorded in the field area and their relationships to each other.

The Sierra Nevada was repeatedly glaciated during the Quarternary (Bateman and Wahrhaftig, 1966). Material was eroded from above the Donner Summit pluton, and subsequently, the outcrop exposures seen today were smoothed and rounded. Weathering from snow, ice, water and other seasonal elements have enhanced the smoothness of the outcrops in recent time. Although the exposures of granodiorite may be outstanding, often it is difficult to obtain a three-dimensional view of dike orientations and cross-cutting relationships given the planar, nearly horizontal exposures.

Measurements of the strike and dip orientation of the felsic and mafic dikes were collected from all three sites in the field area. Only the measurements collected from felsic dikes were plotted on stereonets used in the thesis. A Brunton compass was used for these measurements and readings were taken by directly siting on the outcrop. These measurements were also used for geometric calculations (Z. Reches, personal communication), which are explained later in the thesis. A certain amount of error arises from measurements of the dike dip, i.e. apparent verses actual dip. In all cases the dip was only measured from dikes with a clear-cut three-dimensional view, so that true dips, not aparent dips, were recorded.

Dike deformation was studied in detail for this thesis. Measurements of dilation, shear displacement and oblique movement were taken along the dike plane. In Figure 4

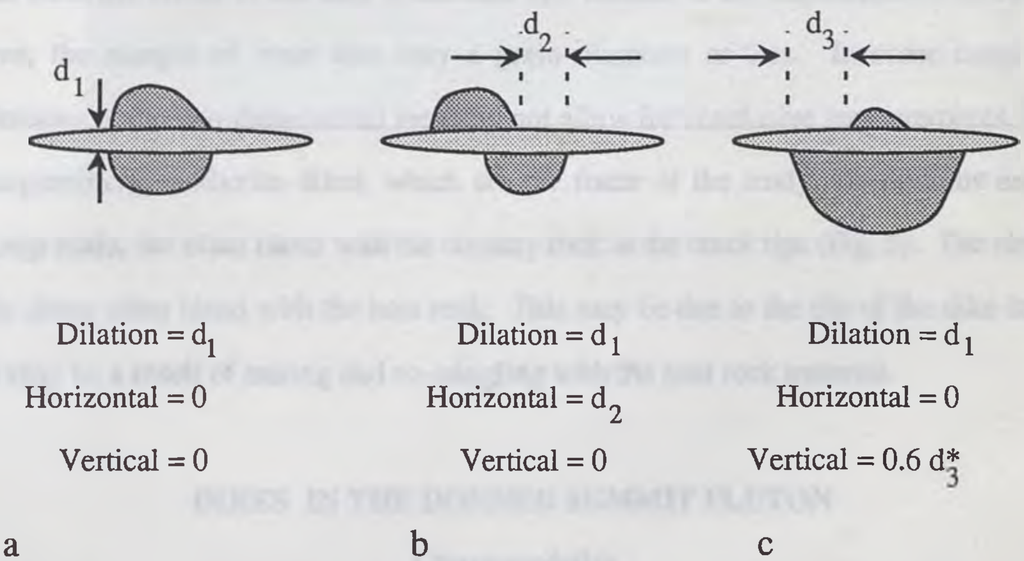


Figure 4. Diagram showing senses of displacement across dikes. (a) Dike with pure opening displacements (dilation) and no shear offset. (b) Dike with both dilation and horizontal (relative to outcrop surface) shear offset. (c) Dike with both dilation and apparent vertical shear offset. Magnitude of apparent vertical offset obtained from d_3 assuming spherical inclusion geometry to first order. The vertical movement was observed but not measured in the field.

different senses of movement that were observed in the field along the dike plane are illustrated as d_1, d_2, and d_3. The regularity of the mafic enclave shapes in the field, as can be readily observed at the Big Bend/Rainbow Road site, was used as a passive marker to measure the apparent offsets. The measurements shown in Figure 4 were collected from all three outcrops. The displacements were measured in centimeters and millimeters. The margin of error only amounted to a grain diameter ($\pm$ 2 mm). The displacements were measured more than one time at all the outcrops. The final results are not compromised by the margin of error in the measurements, because the error was negligible when plotted on the graphs and plots. In addition to displacements along the dike plane, measurements of the dike tip profiles were taken for later analysis.

Dike, exfoliation fracture and blast fracture tip profiles were measured in several steps. First, the length of the dike was recorded. Second, dilation measurements were taken from the center of the dike to the dike tip. Similar to the displacements discussed above, the margin of error was only a grain diameter or less. In some cases the limitations of the two-dimensional view did not allow for conclusive measurements. The leucogranitic/granodiorite dikes, which are the focus of the study, are obvious on the outcrop scale, but often blend with the country rock at the crack tips (Fig. 5). The simple felsic dikes often blend with the host rock. This may be due to the dip of the dike itself, or it may be a result of mixing and co-mingling with the host rock material.

DIKES IN THE DONNER SUMMIT PLUTON

Characteristics

Two principal types of dikes are found in the field area. The first type are "simple dikes" consisting of only one type of material. This material ranges from a leucogranite

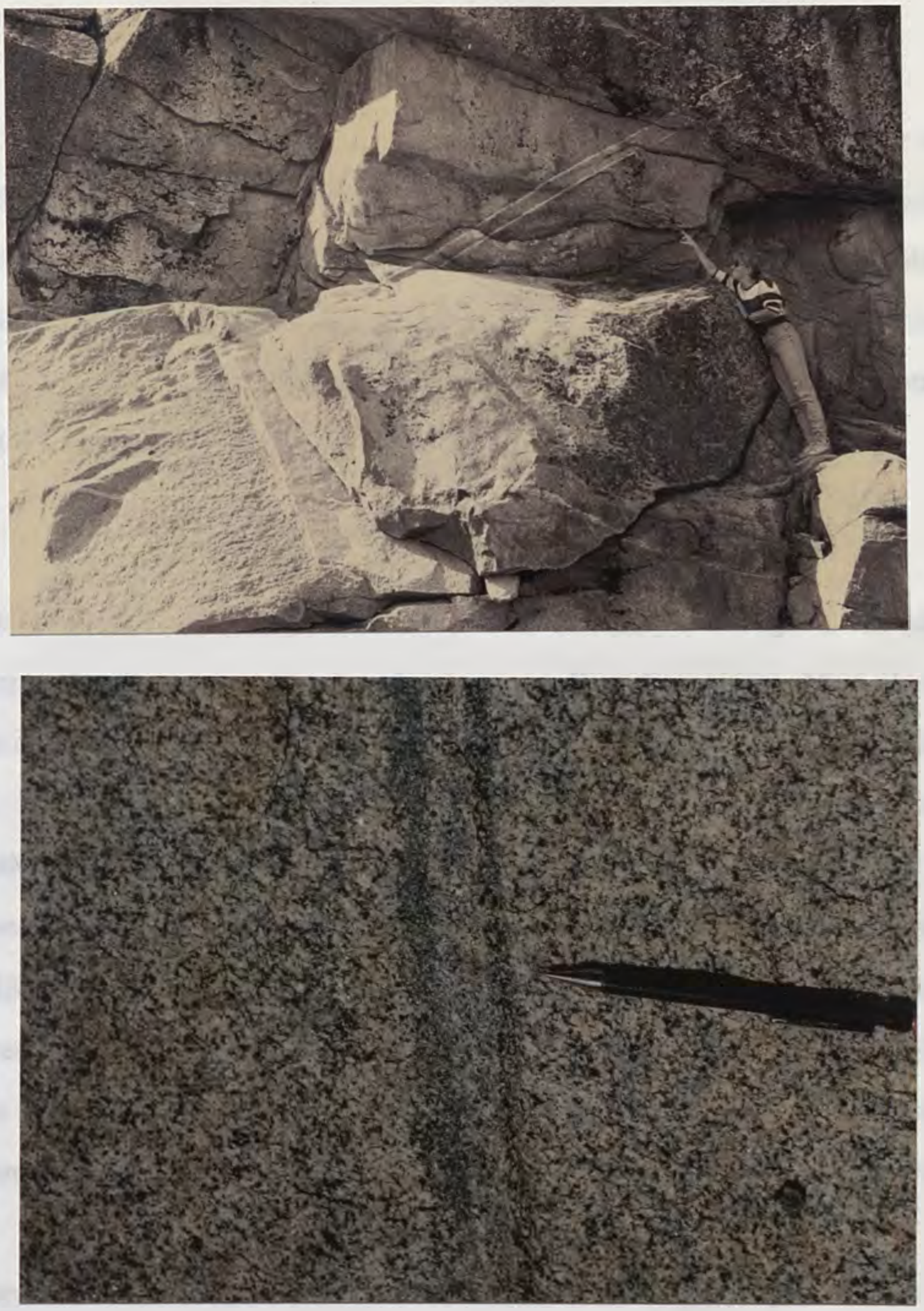
Figure 5. The photo shows a mafic enclave at the Kingvale site with two felsic dikes cross-cutting it. The lens cap is in the position where the top felsic dike blends into the country rock. This apparent blending could be the result of the limited two-dimensional view of the outcrop, suggesting the dike is now below the surface of the outcrop. However, the blending could also support evidence that the dike material is genetically-related to the pluton host rock.

and granodiorite (felsic) to a mafic composition (Fig. 6). The simple dikes are the dominant structures in the Donner Summit pluton.

The second type of dikes are the "complex dikes" which have pegmatitic material along the outer edges of the dike, while the inner portion of the dike consists of a more mafic phase ("felsic-mafic" dikes) (Fig. 7a). There are also examples of reversed "complex dikes" where the inner portion is the more felsic phase (Fig. 7b). Reid and Hamilton (1987) reported similar occurrences of reversed "complex dikes", which they referred to as composite dikes, in a pluton in the southern Sierra Nevada. The pegmatitic portion of their dikes was interpreted to be associated with fracturing through a hot pluton. while the mafic central portion of their composite dikes was thought to have been injected later under cooler conditions into the pre-existing pegmatite dikes. However, the mechanical significance of the complex dikes was not examined by Reid and Hamilton (1987) and no one has studied either type of complex dike in the Donner Summit pluton.

Several field observations support the supposition that dike material was intruded into an incompletely crystallized pluton (Hibbard and Watters, 1985). The borders of a typical simple dike at the grain scale are characterized by interlocking grain boundaries with the host rock. If the hot dike material had intruded into an already cooled host rock there would be evidence of sheared and truncated crystals at the host-dike interface where brittle fracture of the host rock minerals would occur (Hibbard and Watters, 1985). There are also no noticeable chill margins along the length of the dike plane, as were noted by Rogers and Bird (1987) for mafic dikes intruding the Skaergaard complex, East Greenland. A chill margin would most likely form only if a hotter dike material intruded into a cooler host rock and cooled quickly. Thus the temperature differential between the molten dike material and granitic host rock in the Donner Summit pluton apparently was

Figure 6. Field examples of the different types of simple dikes that are found in the Donner Summit pluton. The top photo shows a simple felsic dike cross-cut by another simple dike at a different orientation. The bottom photo shows a T-junction of simple mafic dikes. The dike which stops abruptly at the junction is younger.



A

B

Figure 7. This shows examples of complex dikes in the Donner Summit pluton. (a) The top photo shows a complex dike with the mafic material bordered by a felsic rim. (b) This is the opposite of the first photo with the felsic material bordered by a mafic rim.

not great enough for a chill margin to develop. Fracturing of granite in this manner can occur at relatively high temperature (800°C) for a pluton containing as much as 30–35% volume melt (van der Molen and Paterson, 1979; Hibbard, 1980; Arzi, 1978).

The material contained within the simple dikes is compositionally similar to the material of the host granodiorite as found by chemical and isotopic studies (Hibbard and Watters, 1985). The dike material may be a fraction of the partial melt (M.J. Hibbard, personal communication). Genetically-related material infilling fractures and forming an interlocking fabric with the host plutonic rock constrains the timing of dike emplacement. Dike emplacement occurred during later stages of pluton solidification.

Geometry and Orientation

Dike Orientation; etc. There is a variety of dike orientations throughout the pluton. Commonly the dikes cross-cut each other in a complicated sequence. More than one episode of fracturing and/or dike injection is subsequently recorded in this granodiorite pluton. Figure 8 is an equal area stereoplot of the strike/dip of dikes measured in the three selected sites. There does not appear to be any one dominant direction for these structures. The majority of the dikes are dipping steeply at angles of 70–90°, although many dikes dip at lower angles of approximately 10 to 30°. In some cases the outcrop view was limited to two dimensions, so it was impossible to determine the actual dip on the dike without damaging the outcrop by drilling or other means. The plotted strike and dips were ones that were accurately measured, they represent true values, not apparent.

Geometry. The dikes range in dilation width from a few millimeters up to a meter. The width measurements are a collection of both apparent and true width. There is no en echelon geometry in the simple felsic dike segments as noted by workers studying similar

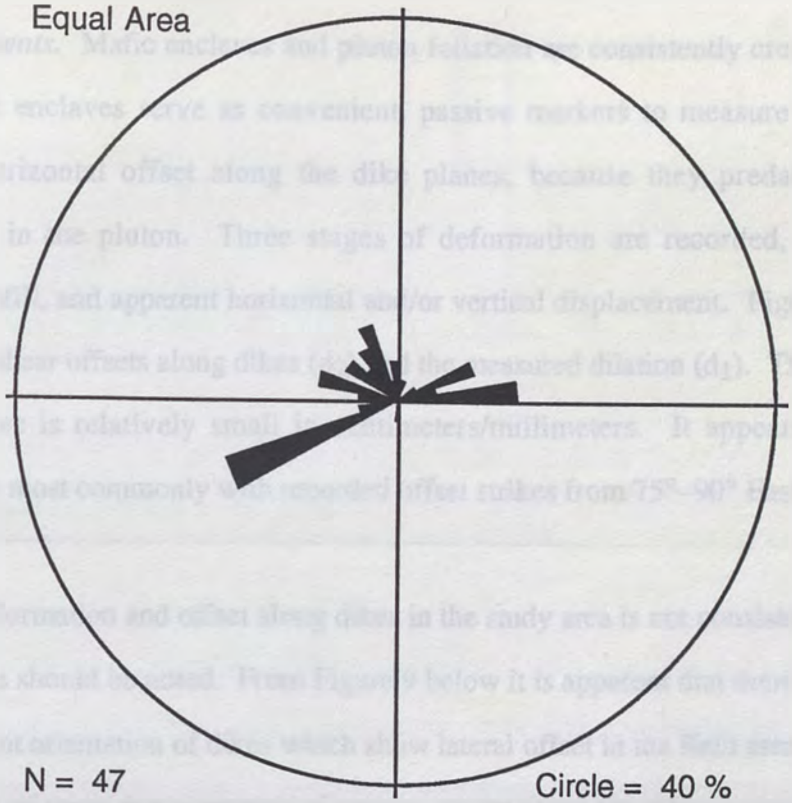


Figure 8. Equal area rose diagram of the strike and dip orientations of dikes from the Donner Summit pluton. Forty-seven readings from all three selected sites are plotted.

features in the southern Sierra Nevada (Segall and Pollard, 1983a). Instead the dikes are planar and continuous for up to several meters in the horizontal direction, and criss-cross the outcrop in a complicated fashion. From road sidecuts it appears that these dikes are also continuous for several meters in the vertical direction too.

Displacements. Mafic enclaves and pluton foliation are consistently cross-cut by dikes. The mafic enclaves serve as convenient, passive markers to measure the amount of vertical/horizontal offset along the dike planes, because they predate all the dike formation in the pluton. Three stages of deformation are recorded, which include dilation, infill, and apparent horizontal and/or vertical displacement. Figure 4 shows the measured shear offsets along dikes (d_2) and the measured dilation (d_1). The displacement of the dikes is relatively small in centimeters/millimeters. It appears that the dike orientation most commonly with recorded offset strikes from 75°–90° East.

Deformation and offset along dikes in the study area is not consistent and several distinctions should be noted. From Figure 9 below it is apparent that there may be a predominant orientation of dikes which show lateral offset in the field area. The occurrence of shear displacements of various senses along the dikes is unusual because it shows that lateral movements of at least several centimeters in any of three dimensions have occurred in conjunction with, or following, late-stage fluid migration within the pluton. From Figure 9 (right panel) it appears that larger shear offsets are found along dikes having nearly east-west strikes. The dilation of the dikes shows a range of opening from 0–30 centimeters, and there appears to be no relation between dike dilation magnitude and dike orientation.

Another distinction is when dikes which have a measurable apparent strike-slip offset are adjacent to dikes with no apparent offset. Also a dike with a measurable lateral offset at some point along its length, will not necessarily show a constant offset along its entire length. Lateral offsets (shear) shown by passive markers can be up to several

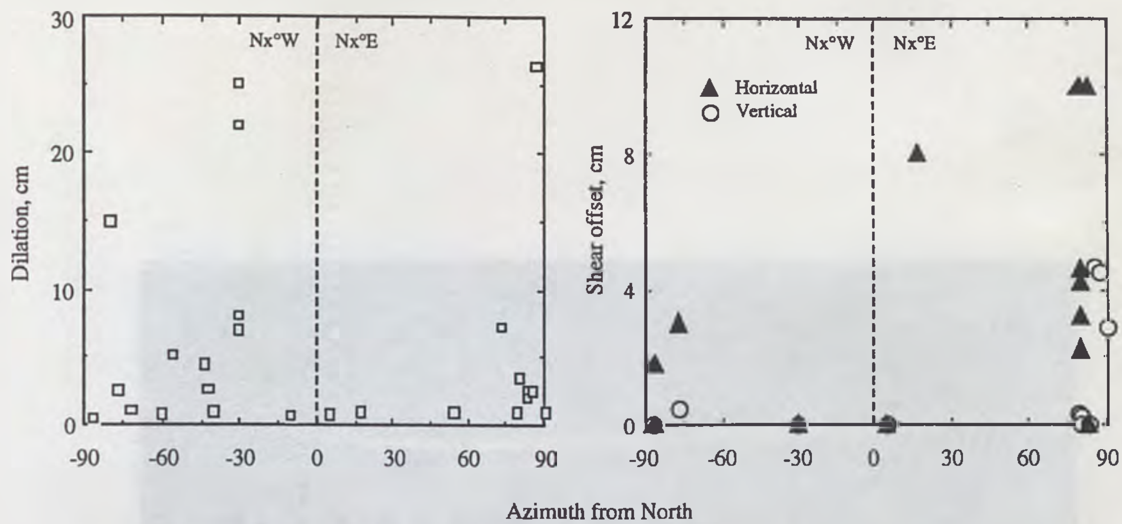


Figure 9. Plots of opening (left panel) and localized shear displacements (right panel) along dikes in the Donner Summit pluton. Larger localized shear offsets tend to be found along dikes having nearly east-west strikes.

centimeters in length. In some cases along the same dike, other markers are not offset laterally (Fig. 10) Thus the shear offsets along many dikes are "localized". This observation requires that significant gradients in shear strain are present in the host rock adjacent to these dikes. These observations are discussed later in the thesis.

Field Structures Helpful in Determining Displacements along Dikes

Accompanying the dikes in the pluton are several structural features which help to interpret the senses of displacement along the dike plane.

Foliation

Primary foliation is present in the pluton, defined by regularly-shaped oval to circular mafic inclusions and elongate crystals (Fig. 11). The inclusions and prismatic

Figure 10. Example of localized offset along a felsic dike. A 40 cm portion of a dike at the Donner Summit observation site has lateral displacement along one part (right side), but is not displaced along its entire length (left side).

Figure 11. The foliation in the Donner Summit pluton is shown not only by mineral grains, but is also defined by mafic enclaves. This photo shows the flattening of the enclaves in the direction to foliation.

crystals parallel the foliation, but the crystal being smaller may show more subtle variations in the foliation than the inclusions do. The foliation is subtle in the Donner Summit pluton. It is more obvious to note the directionality of the inclusions as the foliation in the outcrop, because the crystals in thin section reveal little difference in the direction of the foliation. The dikes cross-cut foliation planes in the host rock (Pabst, 1928; Barbarin, 1990). The cross-cut foliation planes indicate the dikes were intruded during the late stages of pluton emplacement after the foliation had formed in the pluton.

Mafic Enclaves

Field observations of the interaction between cross-cut enclaves and other dikes have helped provide a more complete picture of the dike mechanics. Many of the plutons in the Sierra Nevada batholith are composed of granodiorite and similar compositions and have mafic inclusions (Bateman and Wahrhaftig, 1966). These inclusions range in size from a few centimeters to a meter or more. They are very regular in shape and appear circular or ovoid in two dimensions. Srogi and Lutz (1990) did a three-dimensional study of the inclusions found in the Cretaceous igneous complex at Ascutney Mountain, Vermont. They detemined that three-dimensional manifestations of the inclusions can have very complex shapes. At the field area I have found that the inclusions observable in the 3-d sense have a spherical or elliptical, quite regular shape. In the Donner Summit pluton where these mafic inclusions have been studied, the shape of these inclusions appears to define the predominant foliation (Fig. 11). A deformation relationship to the magma as it was emplaced is possibly related to the directionality of the enclaves (Ramsay, 1989). In areas where the enclaves have been apparently flattened, no systematic work has been completed to note how their morphology might relate to the deformation of the Donner Summit pluton. In this study the mafic inclusions are primarily used as passive markers to measure shear displacement along the dikes planes where the inclusions are cross-cut by the dikes.

Fractures and Dikes Used as Offset Markers

Not only enclaves can be used to measure the relative timing of displacement, but other dikes and fractures can be used as well. The cross-cutting relations such as those shown in (Fig. 12) are indications of the variety of timing relationships found in the Donner Summit pluton. The dikes examined in the outcrops of this study do not extend outside the pluton boundary and are only an internal feature of the Donner Summit pluton. Joints in the southern plutons of the Sierra Nevada batholith are found cross-cutting pluton boundaries (P. Christensen, personal communication). This is further evidence that the fractures formed during the late-stages of pluton formation and not after the pluton had solidified adjacent to the neighboring country rocks.

Late stage fractures of several meters in length and <1cm in width cross-cut most of the field structures. The width of these fractures is probably not the actual dilation, but has been enhanced by weathering. These small fractures do not have any shear displacement along their length. This is determined from the lack of splay cracks at the tip of the fractures and the absence of offset markers such as crystals. The margins along the plane of the fractures appear to have a white cast to them. Hotter hydrothermal fluids may have invaded these fractures in the cooler host rock and formed a baked zone along the crack length. Material present in these fractures now is epidote and chlorite, which is most likely the result of late-stage hydrothermal fluids moving through the pluton. These fractures are similar to those described by workers in the southern Sierra Nevada (Segall and Pollard, 1983 a,b; Martel et al., 1989)

Figure 12. This photo taken from the Donner Summit site shows a complicated cross-cutting sequence of felsic dikes. There are also later exfoliation fractures which in turn cross-cut the dikes. Scale is shown with a lens cap 5.5 cm in diameter.

Also present in the field area are exfoliation fractures. These shallow crustal features are presumed to have developed over recent time at depths of less than 100 meters as a result of frost-wedging, water migration and weathering of the granodiorite along planes of weakness (Johnson, 1970). These fractures range in length from a meter to tens of meters. Large slabs of granodiorite are easily dislodged and appear like onion layers on the outcrops (Fig. 13).

In contrast to these features are the very near-surface man-made blast fractures (Fig. 14). These fractures tend to be shorter in length than the exfoliation fractures and are concentrated in areas where road cuts are located. The fractures tend to radiate out from certain points in the outcrops and are fairly obvious to locate and measure. There is noticeable crack tip branching off from a main crack, formed from dynamic growth of the fractures (Engelder, 1987). Crack tip branching can form from the local stress intensity factor at the tip of a crack being extremely high and secondary cracks form in a process zone at the crack tip. Subsequently, the main crack will branch out to follow the pathway of the secondary cracks. These fractures were not measured. Instead measurements were taken from fractures which grew quasi-statically. Quasi-statically grown fractures will more closely approximate the growth of the dike fractures and exfoliation fractures.

PROBLEMS ADDRESSED

Mechanism for Shear Displacement Along the Dikes

Enclaves in the Donner Summit pluton are cross-cut in a complicated fashion by several generations of dikes. The enclaves, used as passive markers since they predate the injection of the dikes, show strike-slip displacement (Fig. 15). The displacement occurs along the dike plane, but may not be consistent in magnitude or sense of displacement along the entire length of the dike. Figure 10 illustrates a dike which cross-

Figure 13. Large slabs of granodiorite appear like onion layers peeling off of selected outcrops. These slabs are created by the exfoliation fractures. In some cases, a three-dimensional view of mafic enclaves can be found where slabs have broken away from the outcrop face (far right corner with pencil).

Figure 14. Man-made blast fractures are the most recent of the of the fractures formed in the Donner Summit pluton. These are located on outcrops adjacent to the roads. The pencil shows the scale for these fractures.

Figure 15. Mafic enclaves provide a passive marker to illustrate the lateral offset along the dike plane. The dilation of the dike and the lateral offset is less than 5 cm. The toast is white Wonder bread for scale and was used because we made toast of this offset example by drilling cores along the entire length of the dike.

cuts two enclaves within <1m of each other. One of the enclaves shows shear offset of approximately 1 centimeter (Fig 16a), while the other enclave is only separated by the dilation of the dike (Fig. 16b) with no shear offset.

Both experimental work (Ingraffea, 1987) and theoretical work (Lawn and Wilshaw, 1975; Pollard and Segall, 1987; Martel and Pollard, 1989) show splay cracks will preferentially grow parallel to the local direction of maximum compressive stresses. Along fault planes there is expected to be the development of splay cracks at the fault ends, due to the mode II shear that has occurred along the length of the dike plane. At observable crack tips in the Donner Summit pluton there are no splay or wing cracks present (Schultz and Ward, 1993). Splay or wing cracks are commonly seen at the end of fractures that have slipped (Engelder, 1987). It is evidence for mode II failure of the rock (shear) whereas dilation of a fracture is mode I growth. There is a notable absence of splay cracks along these dike planes and their ends.

There are several possible models to explain the lateral or shear offset shown by the mafic enclaves, and the absence of splay cracks at the dike tips. The two most likely models are evaluated below. One model suggests that the shear offset is due to oblique dilation of the dike. When the remote stress is tensile and at an oblique angle to the plane of the dike, an apparent shear offset occurs. The second model suggests that there is localized region along the dike plane which has frictionally slipped. There is not slip along the entire length of the dike plane, but only along a limited extent of the fracture.

Oblique Dilation Model. Reches (personal communication, 1993) suggests that the offset is only apparent due to the dilational displacement along the dike plane. As a dike changes orientation the direction of the remote stress will remain constant and therefore an enclave will appear as if there is a shear displacement in a two-dimensional view.

A

B

Figure 16. This figure shows the mafic enclaves which are found 40 cm apart in Fig. 10. (a) The top photo shows a mafic enclave with localized shear offset along the dike plane. the offset is approximately 1 cm. (b) The bottom photo shows a mafic enclave offset only by the dilation of the dike.

This geometry is shown in Fig. 17. It is easy to solve this geometry to calculate what the orientation change in the dike would have to be to yield the measured shear offset in the field. The model requires that for a given amount of apparent shear offset, there will be a corresponding change in orientation of the dike plane in relation to the constant remote stresses acting on the dike. The remote stress is shown perpendicular to the plane of dike

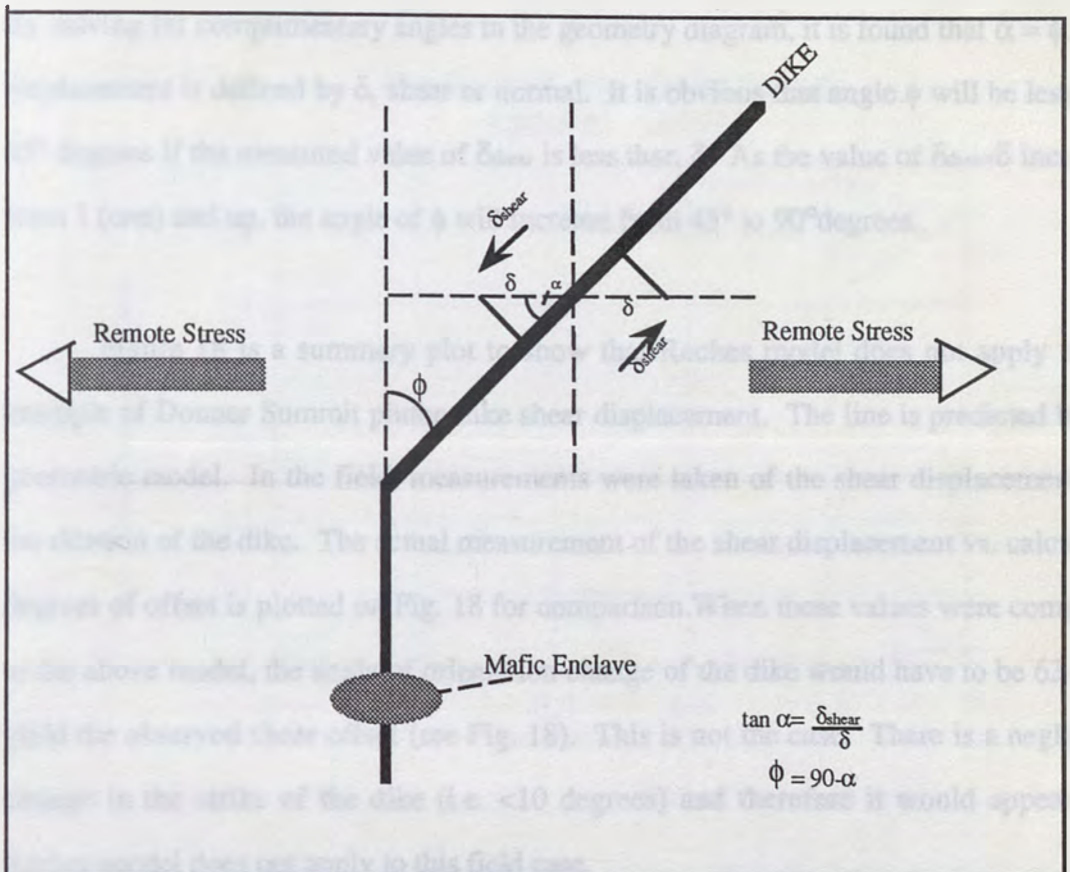


Figure 17. Diagram illustrates the geometry of the model suggested by Reches (personal communication) for oblique dilation. The dike (heavy line) changes orientation, while the remote stress direction remains constant with respect to the dike plane. The result is an apparent strike-slip displacement of an enclave along the dike plane.

separation. Dike dilation occurs normal to the least compressive stress as shown in the Fig. 17. As the dike changes orientation, the remote stress direction probably remains the same over at least a small area (<1-2 meters). When there is no shear displacement along the length of the dike the angle ϕ will be equal to 0 (zero). From equation (1) below (see Fig 17) the expected angle of dike direction change can be calculated using the measured δ_{shear} .

$$\tan \alpha = \frac{\delta_{shear}}{\delta_{normal}}, \alpha = \Phi \tag{1}$$

By solving for complimentary angles in the geometry diagram, it is found that $\alpha = \phi$. The displacement is defined by δ, shear or normal. It is obvious that angle ϕ will be less than 45° degrees if the measured value of δ_{shear} is less than δ. As the value of δ_{shear}/δ increases from 1 (one) and up, the angle of ϕ will increase from 45° to 90°degrees.

Figure 18 is a summary plot to show that Reches model does not apply to the example of Donner Summit pluton dike shear displacement. The line is predicted by the geometric model. In the field, measurements were taken of the shear displacement and the dilation of the dike. The actual measurement of the shear displacement vs. calculated degrees of offset is plotted on Fig. 18 for comparison.When these values were compared to the above model, the angle of orientation change of the dike would have to be 63.4° to yield the observed shear offset (see Fig. 18). This is not the case. There is a negligible change in the strike of the dike (i.e. <10 degrees) and therefore it would appear that Reches model does not apply to this field case.

Slip Patch Model. Martel and Pollard's (1989) work in the southern Sierra Nevada, Mt. Abbot quadrangle, took into account fracture mechanics and elasticity theory to determine how slip could occur along a specific portion of a fracture plane, similar to what is observed along certain dikes in the Donner Summit pluton. Martel and Pollard (1989) have proposed a model of a shear displacement discontinuity or 'slip patch'. The characteristics of the 'slip patch' are shown in a diagrammatic sketch (Fig. 19). This

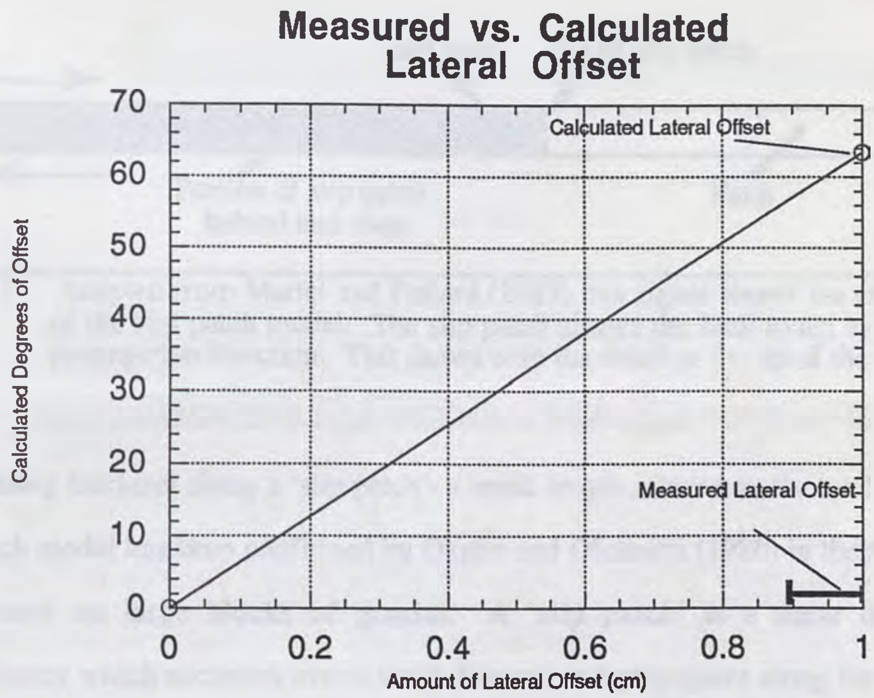


Figure 18. This plot shows the amount of lateral offset vs. calculated degrees of change in dike orientation. On this graph the actual measured offset from field observations is recorded. The line shows the calculated lateral offset using the geometry from Fig. 17.

suggested mode II shear crack nucleates over a small distance of the fracture plane (or fault zone, as shown in the Fig. 20) due to local inhomogeneities in stress or fault properties. The fracture does not slip over the entire length, but essentially, acts as a guide for the 'slip patch'. They proposed that localized shearing would occur on

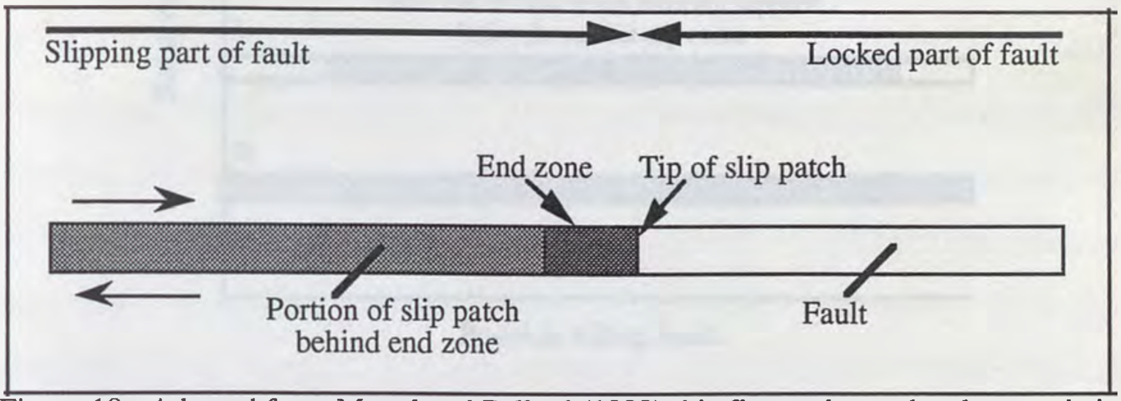


Figure 19. Adapted from Martel and Pollard (1989) this figure shows the characteristics of the slip patch model. The slip patch allows the fault to act as its guide for propagation direction. This shows only the detail at the tip of the slip patch.

pre-existing fractures along a 'slip patch', a small length relative to the total length. The slip patch model has been confirmed by Okubo and Dieterich (1986) in their direct-shear experiment on large blocks of granite. A 'slip patch' is a shear displacement discontinuity which nucleates over a small distance and propagates along the fracture in a quasi-static fashion. Splay cracks will only develop if a patch extends to the fault terminations or if patches on adjacent faults interact. This gives a possible explanation for the lack of splay crack development along the dikes.

> "The formation of a splay crack would be favored if the fracture energy release rate required for continued slip patch propagation [G^{shear}]became locally greater than that required for splay crack formation [G^{splay}]."(Martel and Pollard, 1989)

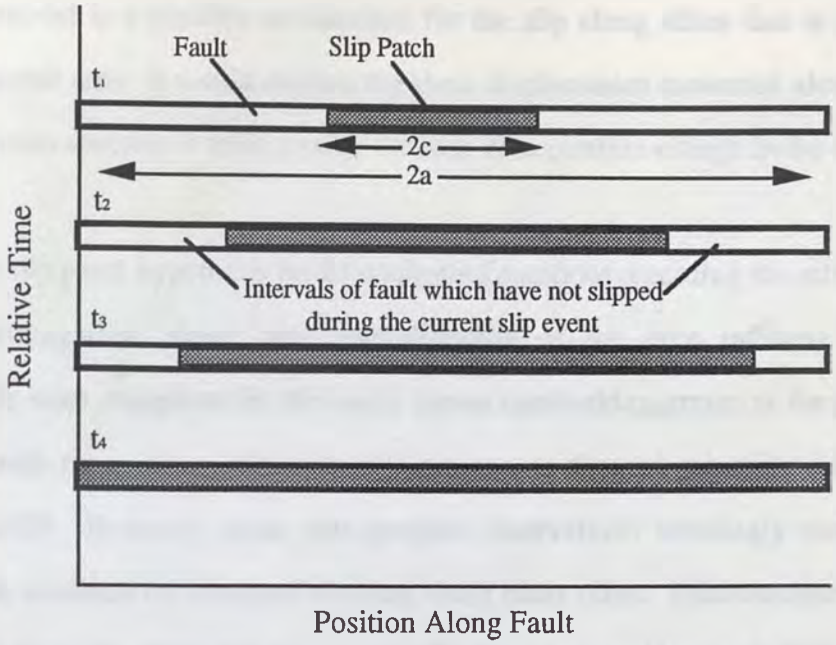


Figure 20. Representation of the nucleation (time t_1) and propagation of a developing slip patch (times t_2—t_4). In this figure (adapted from Martel and Pollard, 1989) a slip patch of length 2c originates on a fault plane of length 2a. The slip patch propagates, and not the fault zone, which acts as a guide for the slip patch.

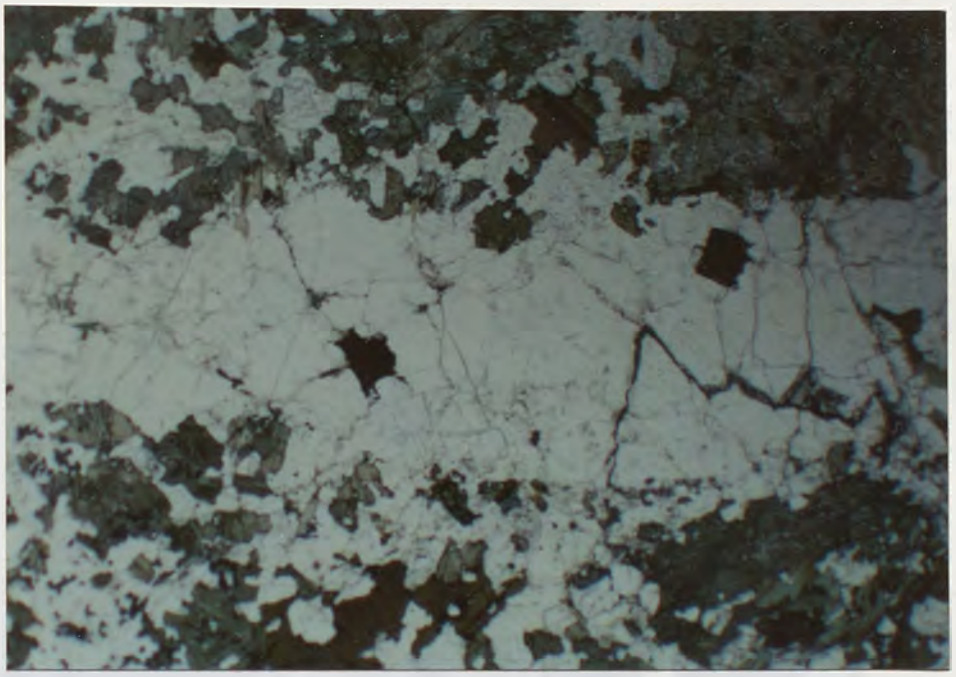
According to Martel and Pollard (1989) the absence of splay cracks indicates that the energy required for propagation exceeded the energy that would be required to form the splay cracks: $G^{shear} > G^{splay}$ and that the end zone, shown in Figure 19, is not fully developed. The latter can occur for 2c approximately equal to 2a.

Applied to the dike examples in the Donner Summit pluton, there is useful insight regarding the mechanism for slip along the dikes. Propagation of slip patches along dike walls appears in this case to be easier than local tensile cracking, and mechanical interaction between slip patches is negligible. The mechanical interaction is negligible because the dikes are widely separated from each other. In addition the localized extent of shear offset along the dike implies that the 2c<<2a, so splay cracks need not form. The slip patch model is a possible explanation for the slip along dikes that is seen in the Donner Summit area. It would explain the shear displacement measured along the dike, the conspicuous absence of splay cracks, the lack of orientation change in the strike.

The slip patch hypothesis raises interesting questions regarding the relative timing of dike propagation, shear, and crystallization of the dike infilling materials. Petrographic work completed in this study shows interlocking grains at the pluton-dike interface, with no evidence of truncated, strained or sheared minerals (Hibbard and Watters, 1985). However, these petrographic observations seemingly contradict the macroscopic evidence for localized shearing along many dikes. Macroscopically there is shear offset along the dikes, but microscopically there is no evidence of shear. Figure 21 shows petrographic slides (plane and polarized light) of cores that were taken from the field area on a dike which had apparent macroscopic shear displacement. There are no sheared or truncated minerals. Additionally, the unsheared, interlocking minerals within the dike plane suggest that slip occurred before complete solidification of the host granodiorite and dike (Hibbard and Watters, 1985). To confirm that there is no shearing in the dike minerals, scanning electron microscope (SEM) photos were taken (Fig. 22).

In contrast to the lack of sheared minerals in the Donner Summit pluton, Martel and Pollard (1989) found sheared minerals infilling the fault zone they studied in the Mt. Abbot quadrangle. The slip that occurred in the Mt. Abbot quadrangle fault zone has happened after complete solidification of material in the faults. The shear displacement along the faults has deformed the infilling minerals.

The mechanism responsible for the shear displacement along the dikes may be the 'slip patch' model proposed by Martel and Pollard (1989). In the Donner Summit pluton



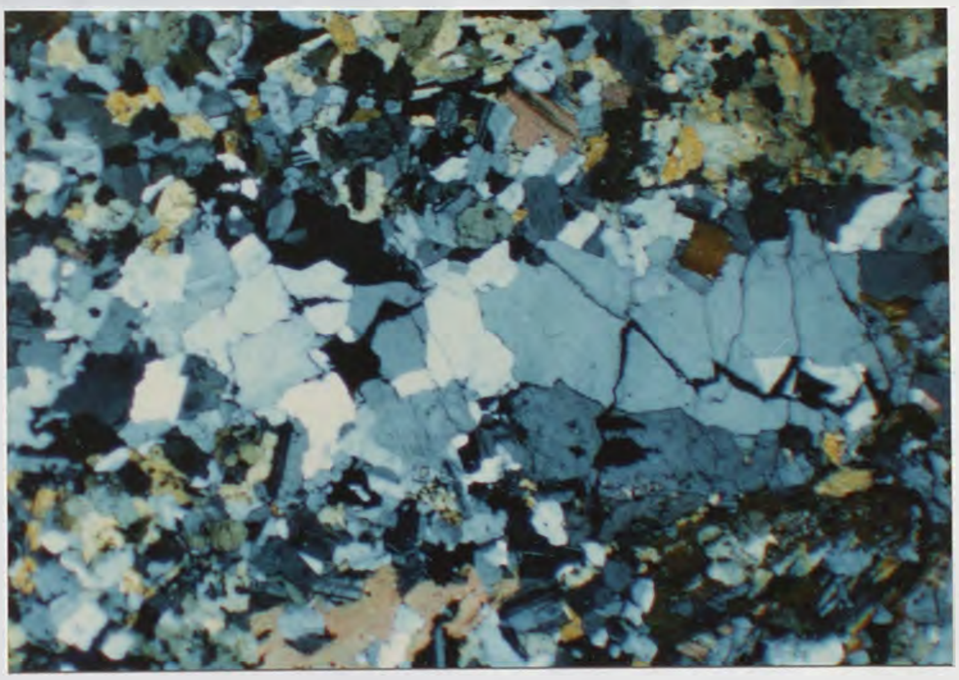


Figure 21. These photos show in plane and polarized light across the dike walls there is an interlocking grain boundary. The dike is oriented east-west in the center of the the photos. The dike is sandwiched between the host rock above and below. There is also no apparent deformations or shear in the dike-infilling minerals (see Fig. 22).

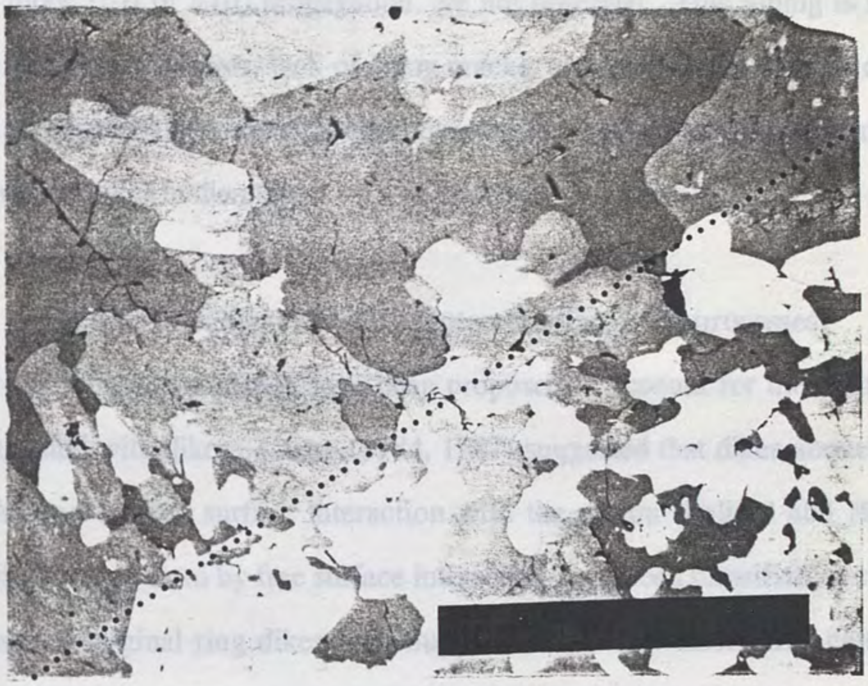


Figure 22. This is an SEM electron micrograph across a grain boundary of a mafic enclave and felsic dike. There is no dike material deformation. The minerals are interlocking and unsheared in the dike and along the interface.

cracking and opening of mode I dikes occurred during late-stages of pluton development, while the pluton was incompletely solidified. Simultaneously or in association with fracture propagation, magma was injected. When localized shearing occurred along the dikes, the dike material was not completely crystallized and an interlocking grain boundary formed at the dike-host interface. However, dike growth was apparently already completed because curved propagation paths, or other geometries characteristic of mixed mode (I-II or I-III) propagation, are not observed. This timing is required to reconcile the offset enclaves, lack of splay cracks, and absence of sheared dike-filling minerals, as proposed by the 'slip-patch' model. It is also consistent with apparent in-plane growth of dikes in the pluton.

Is dike injection related to pluton emplacement processes?

A number of hypotheses have been proposed to account for the dilation and/or shear associated with dikes. Castro (1984, 1987) suggested that dikes above the pluton may be formed by free surface interaction with the pluton (Pollard and Holzhausen, 1979). Dikes which form by free surface interaction have been classified as cone sheets, ring dikes, or marginal ring dikes (e.g. Suppe, 1985). With these three categories the dikes would have a particular dominant orientation related with them. None of these are relevant to dikes in the Donner Summit pluton however, because these terms describe dikes above and outside the pluton body. Castro (1987) also suggests that either radial or concentric dikes may occur within the pluton and near its margin, if the pluton dilates laterally. This fracturing and infilling might occur once the pluton has ascended fully and begun to spread laterally, as suggested by models and experiments of diapiric intrusion (Pitcher, 1979; Brun and Pons, 1981; Marsh, 1982; Castro, 1987, Wickham, 1987; Paterson and Fowler, 1993; Paterson et al., 1991; Petford et al., 1993). Sparks and Marshall (1986) suggested that dike complexes could be associated with magma mixing.

Because these models predict specific types of fractures having characteristic trends and locations within the pluton, results of this study are used here to discriminate between various scenarios for late-stage fracturing of the pluton.

Dikes in the Donner Summit pluton apparently propagated both vertically and laterally. Many mafic dikes exposed in the Big Bend/Rainbow Road subhorizontal outcrops are discontinuous in outcrop view (several to tens of meters in length). These discontinuous dikes found in the outcrops form echelon arrays. However, three-dimensional exposures of these dike arrays suggest that the dikes are more continuous in the vertical direction. The mafic dike exposures are consistent with breakdown of a parent dike at depth as it propagated upward in the pluton.

What model is most applicable to the Donner Summit dikes? There have been some previous suggestions that dikes could have formed in response to simple cooling of the pluton (e.g., Whitney, 1975; Hibbard and Watters, 1985) and several radial dikes (normal to inferred pluton margin) can be observed in certain localities in this pluton. It is difficult to determine the dike orientations in relation to the pluton margin, because the margin, as determined from extensive mapping is not readily measurable as a regularly shaped body. Figure 23 illustrates the dike orientations collected from two of the three selected sites of the thesis research. At this time it is difficult to assess the appropriate model which could relate dike injection to a pluton emplacement process.

Dike emplacement: Passive or Active?

There are two previously proposed models addressed in this study regarding the mechanics of late-stage dike formation in the pluton. Dike material could either have invaded previously-formed fractures or hydraulically-created its own fractures (e.g.

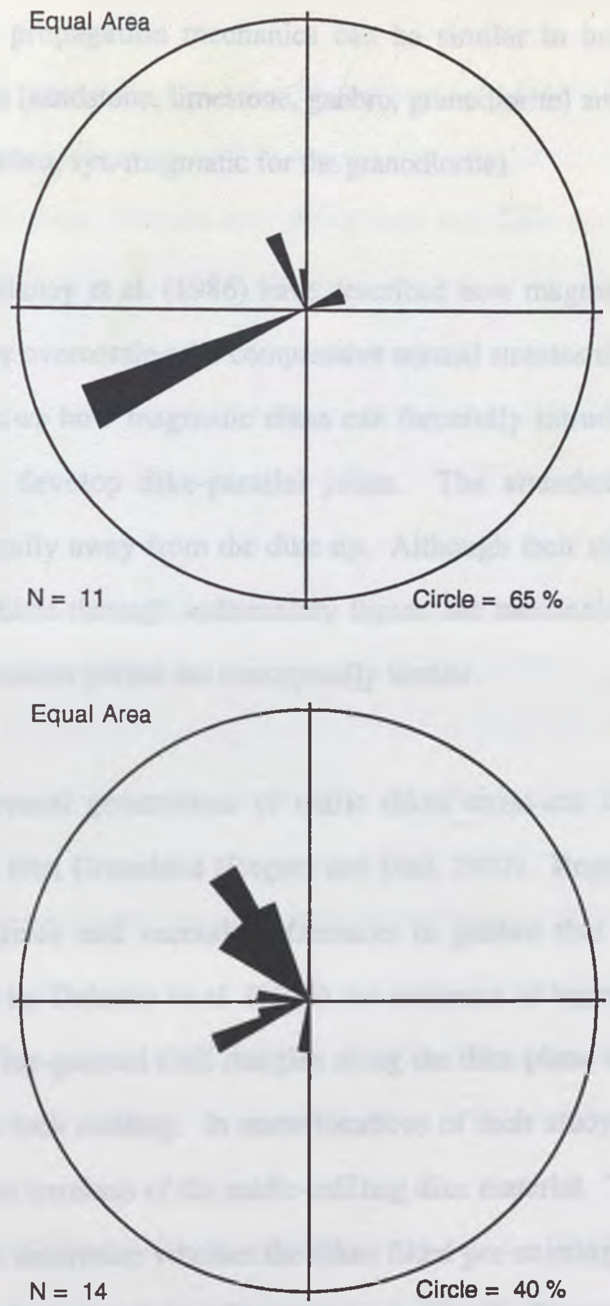


Figure 23. These are stereoplots of two selected areas, Big Bend/Rainbow Road (top) and Donner Summit (bottom), respectively. The dikes plotted from the Big Bend area seem to have a predominant orientation to the southwest. There are only eleven readings to define this orientation. The fourteen dikes measurements from the Donner Summit site illustrate no predominant orientation.

Delaney et al., 1986), and this distinction has been evaluated in the field for the Donner Summit dikes using the criteria of Delaney et al. (1986). Results from this thesis suggest that dike propagation mechanics can be similar in host rocks having a variety of lithologies (sandstone, limestone, gabbro, granodiorite) and temperatures (post-magmatic for the gabbro, syn-magmatic for the granodiorite).

Delaney et al. (1986) have described how magma propagates its own hydraulic fracture by overcoming the compressive normal stresses along the dike plane. Delaney's model shows how magmatic dikes can forcefully intrude into sedimentary rocks and, typically, develop dike-parallel joints. The abundance of these joints decreases systematically away from the dike tip. Although their study focused on propagation of igneous dikes through sedimentary layers, the mechanics of dikes propagating into a partially molten pluton are conceptually similar.

Several generations of mafic dikes cross-cut the gabbro of the Skaergaard intrusion, East Greenland (Rogers and Bird, 1987). Rogers and Bird (1987) have noted process zones and secondary fractures in gabbro that are analogous to the criteria proposed by Delaney et al. (1986) for evidence of hydraulically-created fractures. In addition fine-grained chill margins along the dike plane indicate dike injection occurred after host rock cooling. In some locations of their study the fractures have propagated beyond the terminus of the mafic-infilling dike material. Therefore, it is difficult in these regions to determine whether the dikes filled pre-existing fractures or if the fracture has propagated ahead of the dike as it is emplaced. Rogers and Bird (1987) do describe hydraulic fracturing as a possible emplacement mechanism for the dikes present in the Skaergaard intrusion. In contrast, chill margins are not evident in the Donner Summit pluton. Dike examples from the Donner Summit pluton differ from those in the

Skaergaard because the dikes propagated through the granodiorite host rock before it had cooled completely.

Several indicators used by Delaney et al. (1986) to infer that dikes intruded unfractured rock are found in association with several dikes in the Donner Summit pluton. Previous workers have recognized that dikes such as those in the study area are formed by fluid injection into fractures and not by replacement along rock surfaces (e.g., Hibbard, 1980). Newly recognized extensional fracture geometries ahead of the dike termination found in the Donner Summit pluton (Fig. 24) are comparable to Delaney's model of magmatic pressure creating fractures; a dike-tip process zone.

For example, one particularly clear dike termination in the granodiorite (see Fig. 24) is associated spatially with an array of parallel microcracks (up to a few cm long) that decrease in abundance away from the dike tip (Fig. 25). The dike is several meters long and the microcracks extend to perhaps 1 m beyond the dike tip. These secondary cracks are also filled with igneous material similar to that found in the dike. We also note a lack of systematic jointing near the dike that might have provided an avenue for passive dike injection. We infer that this dike created its own fracture as it propagated into the granodiorite. Because of the lack of well developed joint sets in the vicinity of other dikes, it seems likely that many other dikes in the pluton also created their own fractures.

What fracture mechanics model applies to dike tip profiles from Donner Summit?

Geologists, geophysicists, and engineers have employed fracture mechanics to learn about processes of rock deformation. Fracture mechanics is especially important when interpreting the mechanism for fracture growth in rock. Inelastic deformation that occurs in the region surrounding propagating fractures creates a host of structures which

Figure 24. This photo shows the extensional fracture geometry which borders and is beyond the main dike tip. The main dike is the thickest dike at the center of the photo extending east-west across the photo. The other smaller fractures infilled with felsic material are the dike-parallel fractures (Delaney et al., 1986).

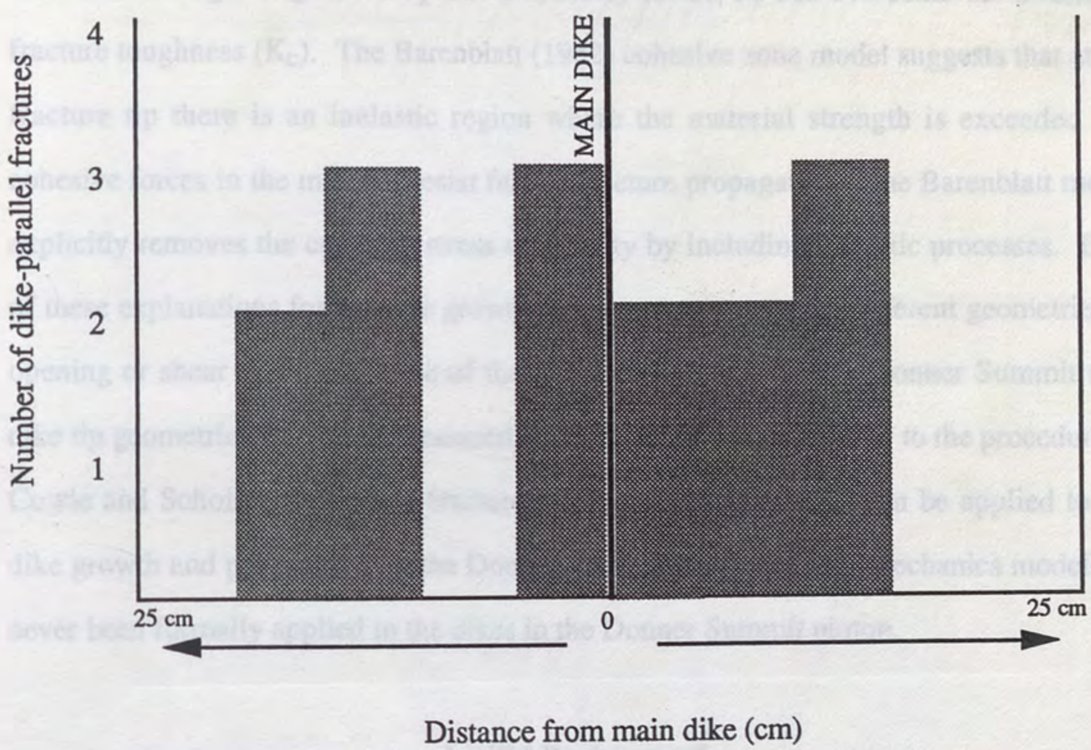


Figure 25. This is a diagram to show the abundance and geometry of the dike-parallel joints from Fig. 24. The main dike is represented by the vertical line in the center of the diagram. To the right and to the left shows the abundance of dike-parallel joints as one moves away from the main dike. Beyond 25 cm to either side of the dike, there are no more macroscopic dike-parallel joints.

have ramifications on the interpretation of processes of dike injection (Rubin, 1993). There are two alternative yet complimentary fracture mechanics explanations to model the emplacement of the infilled fractures of the Donner Summit pluton. LEFM (Linear Elastic Fracture Mechanics) postulated by Griffith (1921) and others state simply that a fracture will grow and propagate as long as the mechanical energy availiable to increase the fracture length (e.g. crack-tip stress intensity factor; K) can overcome the material's fracture toughness (K_c). The Barenblatt (1962) cohesive zone model suggests that at the fracture tip there is an inelastic region where the material strength is exceeded and cohesive forces in the material resist further fracture propagation. The Barenblatt model explicitly removes the crack tip stress singularity by including inelastic processes. Both of these explanations for fracture growth and propagation predict different geometries of opening or shear at the end zone of the fracture (Fig. 26). In the Donner Summit area dike tip geometries have been measured and plotted on graphs, similar to the procedure of Cowie and Scholz (1993), so a fracture mechanics interpretation can be applied to the dike growth and propagation in the Donner Sumit area. A fracture mechanics model has never been formally applied to the dikes in the Donner Summit pluton.

LEFM Background

The theory of LEFM (Linear Elastic Fracture Mechanics) has been used to relate stresses at the tip of an idealized fault or fracture to the energy required for it to propagate. The material at the fault or fracture tip is considered to be elastic for LEFM. According to fracture mechanics for the LEFM theory, propagation occurs when $K \geq K_c$. The crack tip stress intensity factor is equal to or greater than the fracture toughness, respectively (Rubin, 1993; Lawn and Wilshaw, 1975). If the energy availiable from forces such as magma pressure and remote stress is sufficient cracking will occur (Lawn and Wilshaw, 1975; Rubin and Pollard, 1987). LEFM model predicts an elliptical

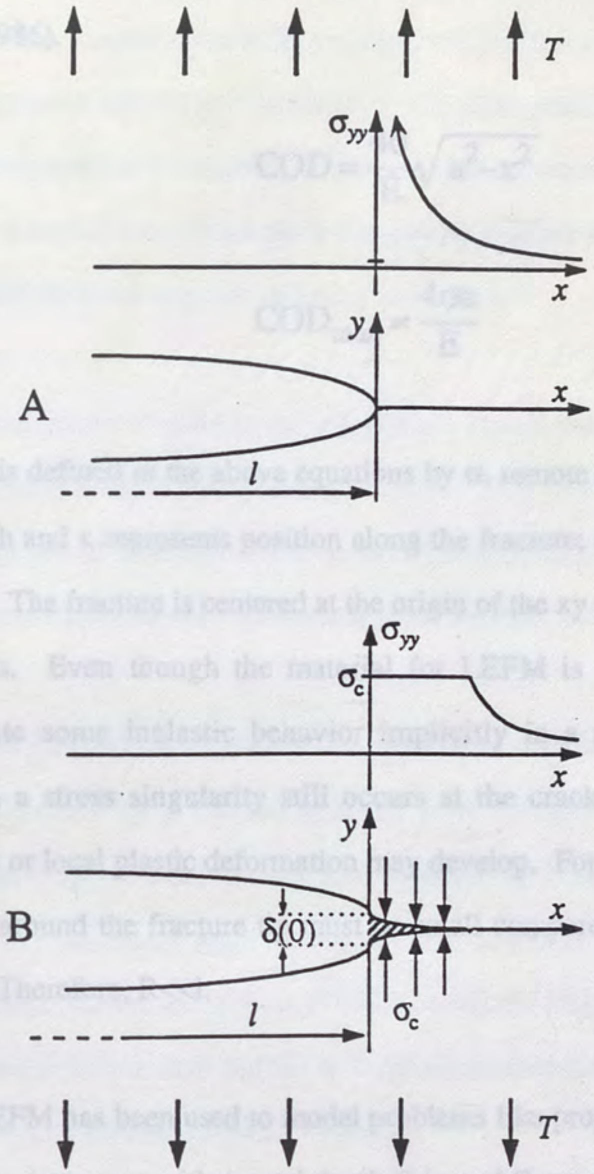


Figure 26. This figure shows predicted fracture tip geometries for LEFM and the Barenblatt-Dugdale model. At the top of the diagram is the elliptical crack tip geometry predicted from LEFM. The crack tip geometry is more tapered and less elliptical for the Barenblatt-Dugdale model (bottom). These were adapted from Rubin (1993). Main features of this diagram are T=tensile stress, l=length of fracture, σ_c=compressive stress and σ_{yy}=yield stress.

displacement distribution, where finite displacement occurs at the fracture tip. The crack opening displacement (COD) along the fracture length is given by equations (2) and (3) (Broek, 1986).

$$COD = \frac{4\sigma}{E}\sqrt{a^2 - x^2} \tag{2}$$

$$COD_{max} = \frac{4\sigma a}{E} \tag{3}$$

COD (δ) is defined in the above equations by σ, remote stress acting on the fracture; a is half length and x represents position along the fracture; and E which represents Young's modulus. The fracture is centered at the origin of the xy coordinate system and lies along the x-axis. Even though the material for LEFM is assumed to be elastic, it does incorporate some inelastic behavior implicitly in a process zone at the crack tip. However, a stress singularity still occurs at the crack tip. In this region secondary fracturing or local plastic deformation may develop. For LEFM the radius of the process zone (R) around the fracture tip must be small compared to the total length (2a) of the fracture. Therefore, R<<l.

LEFM has been used to model problems like propagation of a normal fault as the overburden increases with crustal depth (Lin and Parmentier, 1988). LEFM is normally assumed to be independent of confining pressure. Aydin and Schultz (1990) used LEFM to model whether propagation of a fault would increase or decrease in the shadow zone of another fault segment. Rubin and Pollard (1987) model the dikes they studied as pressurized cracks in an isotropic, homgeneous, linear elastic half space.

Barenblatt-Dugdale Background

Barenblatt-Dugdale developed a cohesion zone model for mode I cracks. In contrast to the elliptical crack tip profile predicted from LEFM, the Barenblatt-Dugdale model suggests a tapered profile (see Fig. 26). This resulting tapered profile requires that inelastic deformation is occurring in the surrounding material beyond the crack tip. There is a small cohesive zone of length R beyond the fracture tip (Rubin, 1993) where internal cohesive forces in the rock are resisting separation.

> "The cohesive zone is the transitional region between broken bonds and unbroken, but highly strained ones. The size of this region gives a measure of a distance over which forces deviate from the predictions of linear elastic theory." (Atkinson and Meredith, 1987)

Still further beyond the crack tip the material is still deforming elastically. The peak stress at the crack tip is refered to as the yield strength. As yield strength approaches infinity, the Dugdale-Barenblatt model becomes equivalent to the LEFM model. Rubin (1990, 1991) considers applications for the cohesion zone model to propagation of igneous dikes. Cowie and Scholz (1993) applied the Dugdale-Barenblatt model to faults. In both cases (dikes and faults) a Dugdale-Barenblatt model was considered more appropriate than the standard LEFM model.

Dike-Tip Process Zone Example

In order to understand how a fault or fracture propagates we need to consider the zone of deformation at the fault tip (Rubin, 1990, 1991; Cowie and Scholz, 1993; Dugdale, 1960; Barenblatt, 1962). In the Donner Summit pluton there are dike-parallel joints evident which suggest according to Delaney's criterion that the dikes propagated into their own hydraulically-formed fractures. The viscosity of the intruded dike material is high in relation to the material that Rubin noted in his 1993 paper. The shape of the dike parallel joints does not approximate expected LEFM fracture propagation criterion. The shape more closely illustrates the Dugdale-Barenblatt model. These dike parallel joints supposedly formed at depths of 5-10 km. Rubin (1993) states that at depths greater than 1 km the large confining pressure renders LEFM invalid, because R may no longer be small in relation to a.

In the Donner Summit pluton I have measured the profiles of several types of fractures. First, I have taken COD measurements of dike-parallel joints in a process zone surrounding a dike tip. These fractures are thought to have formed at depths of 5-10km. Second, I recorded measurements of crack tip profiles from near-surface exfoliation fractures. These exfoliation fractures probably formed at depths not more than 100 meters (Johnson, 1970). Lastly, on the outcrop surfaces, adjacent to roads, there are blast fractures which formed at the surface. The purpose of taking crack tip profiles from cracks which formed at kilometers of depth versus the Earth's surface was to see which model might apply to the propagation of the cracks, LEFM or Dugdale-Barenblatt. By taking readings from fracture tip profiles that formed at different depths it is possible to see if confining pressure plays a role in the predicted model as suggested by Rubin (1993).

The profile measurements were taken along the half length of the dikes. I measured the total length of the dike and then preceded to take width values along the dike until its termination. In the case of the exfoliation fractures and the blast fractures, it would seem that their formation and exposure at the surface or near-surface would lead to weathering conditions, i.e. frost-wedging, water seepage, which would increase the width of the fractures from their original formation width. The profile is assumed to have remained relatively constant except for the width increase. Even so, there is a factor of error that must be considered when regarding the plot of the crack tip profiles. However, regardless of the method of dilation, the crack tip profile (COD) will be diagnostic of either purely elastic (LEFM) or inelastic conditions; so those factors do not change the results presented here. The measurements were taken with a ruler and the width error was no greater than a grain width ($\pm$ 2 mm). The profile of a crack tip can be predicted for LEFM using the following equation, obtained by normalizing equation (2) by (3).

$$\frac{\delta}{\delta_{max}} = \frac{\sqrt{a^2 - x^2}}{a} \tag{4}$$

The curve for LEFM is superimposed on the plots of the actual crack tip profiles measured in the field (Fig. 27). The fracture tip profiles range in depth of formation from 5–10 km to the surface. It appears from the profiles of the fracture tips at any depth, none follow the predicted curve for the LEFM model. Instead these plotted fracture tip profiles follow the more linear trend of the Dugdale-Barenblatt model. Since this is the case, it would appear that the Dugdale-Barenblatt model is one possible explanation for formation of these fractures. The Dugdale-Barenblatt model seems applicable to each case from 5-10 km depth formed fractures to the blast fractures formed at the rock surface. However, the influence of confining pressure can not yet be answered directly because the cohesive zones of the respective fractures can not be resolved by the measurement technique. This could be accomplished by SEM (scanning electron microscope) or other high-precision techniques. Cowie and Scholz (1992) and Rubin (1993) note that the Dugdale-Barenblatt model is more commonly applied to large faults (meters) and fractures, but at the scale of the dikes in the Donner Summit pluton

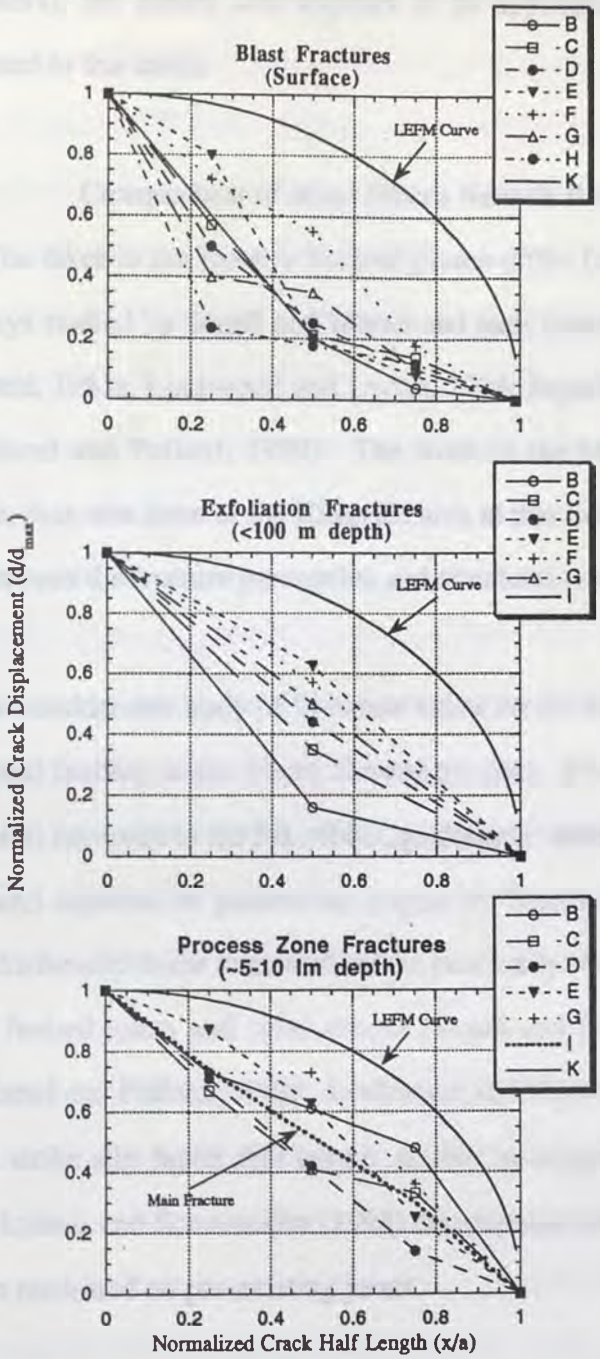


Figure 27. Each of these three graphs shows the plotted dike tip geometries from the three field sites in the Donner Summit pluton. The x-axis of each graph is the normalized crack half length defined by x/a. At the fracture midpoint $^x/_a = 0.0$, while at the dike tip x=a; $^x/_a=1.0$. The y-axis is the normalized crack displacement, which is found by dividing the displacement at a point by the maximum displacement along the crack. The LEFM curve is also superimposed on these graphs to compare the dike tip profiles.

(centimeters), the model also appears to be applicable based on the measurements documented in this thesis.

Comparison of other Sierra Nevada Batholith Research

The dikes in the Donner Summit pluton differ fundementally from the crack and fault arrays studied by Segall and Martel and their coworkers, for several resons (Segall and Pollard, 1983a; Lockwood and Lydon, 1975; Segall and Pollard, 1980; Martel et al, 1988; Martel and Pollard, 1989). The work in the Mount Abbot area is much more extensive, than that done in the Kingvale area at this time. Nonetheless, a comparison is useful between the fracture geometries and structural relationships within the plutons.

A considerable body of literature exists on the field expression and mechanics of jointing and faulting in the Sierra Nevada granites. For example, the growth of dilatant crack (joint) networks in the Mt. Abbot quadrangle located far south of the study area was studied and reported in pioneering papers by Segall and Pollard (1983a) and Segall (1984). Strike-slip faults nucleated on the previously formed joints to produce a complex array of faulted joints and splay cracks (Segall and Pollard, 1980; 1983; Martel et al, 1988; Martel and Pollard, 1989). Lockwood and Moore (1979) documented several sets of small strike-slip faults that appear similar in origin to those studied by Segall and Martel. Lahren and Schweickert (1991) documented Neogene strike-slip faults that may have also nucleated on pre-existing joints.

Several researchers have studied the Mount Abbot quadrangle and documented fracture and fault growth and propagation in relation to other structures. Predominantly, joints have been studied at Florence Lake, Lake Edison, and the Bear Creek area. At Florence Lake, the joints are found in a granodiorite pluton which comprises a portion of the Sierra Nevada batholith (Segall and Pollard, 1983a; Lockwood and Lydon, 1975). The joints have been found to postdate the age of the pluton, probably Cretaceous age or younger (Segall and Pollard, 1983a,b). The steeply-dipping, northeast-trending joints at Florence Lake are dilational. They are thought to have been subject to a regional, tensional stress regime. At some time after the dilatant fractures had formed, they were infilled with epidote, chlorite, and other secondary minerals. The wall rock in the area is hydrothermally altered (Segall et al., 1990) suggesting that fluids moved through the pre-existing fractures leaving the secondary minerals. Shear displacements (faulting) were localized on the fractures sometime after the epidote-bearing fluids stopped circulating and after crystallization, as evidenced by shearing of these crack-filling minerals (Segall and Pollard, 1983b; Segall and Simpson, 1986). These fractures also cross-cut pluton boundaries, suggesting they postdate cooling of the individual plutons and may be related to a more regional stress state (e.g. Lockwood and Moore, 1979; Segall and Pollard, 1983b) The fractures in this study area occur as discontinuous echelon segments (Segall and Pollard, 1980, 1983) because they grew from numerous small flaws distributed throughout that pluton.

Segall and Pollard (1983a,b) looked at the direction and magnitude of surface displacements evident along the joints. They observed cross-cutting relations between mafic inclusions of the pluton and joints present and evidence of shear deformation of the secondary minerals in the fractures. This evidence unequivocably put the age of the infilled minerals after the regional joint dilation. In the outcrop scale there is evidence of joints with displacement and joints without displacement. This preferential strike-separation on some joints and not others suggests progressive shearing due to regional deformation. The development of strike-slip fault zones from pre-existing fractures is clearly demonstrated from field observations (Martel and Pollard, 1989; Martel, 1990).

Certain characteristics of joints are observed at each locality in the Mt. Abbot quadrangle. The joints form joint sets. The joints often found are subparallel and dilational in nature. Lastly, the joints observed are found in finite lengths (discontinuous) (Segall, 1984). Other observations were also made at the Lake Edison granodiorite pluton and in the Bear Creek area. At Lake Edison the fracture geometry varied very little from Florence Lake, and faults had also formed on pre-existing fractures of the region. Similarly, in the Bear Creek area, joints formed and were subsequently displaced. The non-coplanar surfaces of the discontinuous joints are found joined at steps and bends to form a compound strike-slip fault zone (Martel et al., 1988).

The fracture geometry is similar in the northern and central Sierras both in orientation and morphology. Both areas have fractures oriented roughly north-south. The fractures in both areas are dilatant and discontinuous. Both areas appear to have been subject to a regional tension. The cross-cutting relationships in each study area show that the mafic inclusions were present and originated from the pluton, well before fracturing occurred.

There are several differences between the structures studied in the southern Sierra Nevada and the Donner Summit structures. No echelon patterns are observed in the Kingvale area. Instead, the fractures are predominantly oriented ~north-south with other fractures cross-cutting perpendicular to this trend. The fractures in the Mount Abbot area cross-cut adjacent pluton boundaries, while the dikes from the Donner Summit pluton appear not to cross-cut the pluton's margin. This implies that the dike formation occurred only internal to the Donner Summit pluton, and injection did not happen after solidification of the pluton. The material recorded in the fractures of each area also suggests a different mineralogic history and origin. In the Kingvale area, the dike material found in the fractures suggests a genetic relationship to some stage of the pluton's magmatic activity. In the Mount Abbot area, the secondary minerals infilling the fractures seem to originate from some late stage hydrothermal activity, after the pluton was cooled. The relative timing of the dike injection is documented in the Kingvale area to have been at some time during pluton emplacement, while in the Mount Abbot area the infill of fractures is post-emplacement.

CONCLUSIONS

The emplacement and deformation of the dikes in the Donner Summit pluton occurred while the pluton was still partially molten. Dikes were injected into an incompletely crystallized pluton at several kilometers depth. The stages of deformation of these dikes have been documented. Previous work done in this region suggested a complex dike deformational history of dilation, magma infill, and localized shear offset (Hibbard and Watters, 1985). This thesis has confirmed and supported much of the previous work regarding dike emplacement mechanics. In addition, this thesis has taken field observations and applied theoretical models to find that the Dugdale-Barenblatt model for fracture growth and propagation is more appropriate. Dikes cross-cut each other in a complicated sequence suggesting more than one episode of dike intrusion into the Donner Summit pluton. Before complete crystallization of the pluton, localized shearing occurred along the dike planes. After complete solidification of the pluton, exfoliation fractures formed at relatively shallow depths. More recent blast fractures were created in the roadcut faces.

From the field observations, interaction between cross-cut enclaves and other dikes have provided a more complete picture of dike mechanics. In the field a syn-magmatic magmatic enclave is cross-cut by a dilational late-stage fracture which has been infilled with predominantly felsic magma. There is also evidence of an additional component of deformation with fracture dilation, infill, and localized shear offset. The offset is well-defined by enclave displacement. Petrographic work completed in this study shows interlocking grains at the pluton-dike interface, with no evidence of truncated, strained or sheared minerals. These petrographic observations seemingly contradict the macroscopic evidence for localized shearing along many dikes. The boundaries between dike, enclave, and host granodiorite are all distinct with no chill margins. Megascopically in areas of localized shear offset there is no development of wing cracks. Reches (personal communication, 1993) suggested a model in which the change in orientation of a dike would create an apparent localized shear offset in outcrop view. This is not the case for these Donner Summit dikes. The calculated change in dike orientation would have to be 60 times what is observed to yield the offset actually measured in the field. Instead, the localized shear displacement may have formed as the result of a 'slip patch', as suggested by Martel and Pollard's work in the southern Sierra Nevada. Splay cracks will only develop if a patch extends to the fault terminations or if patches on adjacent faults interact. The propagation of slip patches along dike walls was most likely easier than local tensile cracking, and mechanical interaction between slip patches was negligible. Additionally, the unsheared, interlocking minerals within the offset dike plane suggest that slip occurred before complete solidification of the host granodiorite and dike. This timing is required to reconcile the offset enclaves, lack of splay cracks, and absence of sheared dike-filling minerals.

There are two previously proposed models addressed in this study regarding the mechanics of late-stage dike formation in the pluton. One model suggests that magma will invade previously-formed fractures. In contrast, Delaney et al. (1986) have described how magma propagates its own hydraulic fracture by overcoming the compressive normal stresses. Delaney's model as extended by Rubin (1993) shows how magmatic dikes forcefully intrude into sedimentary rocks and, typically, develop dike-parallel joints. The abundance of these joints decrease systematically away from the dike tip. Petrographic analysis and field observations show evidence that the dikes in the field area hydraulically created their own fractures, instead of invading previously-formed fractures. Extensional fracture geometries ahead of the dike termination are comparable to Delaney's model of magmatic pressure creating fractures with infill happening simultaneously. There is a measurable decrease in abundance of dike-parallel fractures away from the main dike. This dike geometry found in the field qualifies as a process zone feature using criteria supplied by Delaney et al. (1986).

There are many possible fracture mechanics explanations which would shed light on the emplacement of fractures in the Donner Summit pluton. Linear Elastic Fracture Mechanics (LEFM) and the Dugdale-Barenblatt model have been proposed in recent papers for fault and fractures propagation in crystalline rocks. Each of these models predicts a different fracture tip geometry. LEFM will show a more elliptical crack tip profile, while the Dugdale-Barenblatt model proposes a more tapered profile. From field measurements taken from three types of fractures which formed at different depths inthe pluton it is possible to predict one fracture mechanics model which applies. The Dugdale-Barenblatt model more closely approximates the dike tip profiles recorded from the Donner Summit area. Tip profiles from dikes, exfoliation fractures, and blast fractures, provided convincing evidence that the Dugdale-Barenblatt model is one model applicable to these fractures independent of confining pressure (crustal depth).

Further Research

Already the interest in the mechanics and kinematics of the Donner Summit pluton has increased in the granite community. A host of problems have been observed and need further study in this field area.

Many questions regarding the emplacement of the pluton itself which could be addressed. Guglielmo (1993) studied pluton emplacement kinematics, focusing on strain patterns, present in the pluton as modelled by evidence of the deformation of structures outside the pluton boundaries. Guglielmo suggests the complexity of the geometry of plutons is related to the interactions between regional tectonic-related and local pluton-related strain fields. Other studies have focused on the possible mechanism of movement of the pluton into the crust itself and the factors that can affect the movement (Brace and Kohlstedt, 1980; Kriens and Wernicke, 1990). Studies of synplutonic dike emplacement have argued that plutons may be emplaced in regions of local or regional extension (Pitcher, 1979; Paterson and Fowler, 1993). There are certainly many important aspects of pluton emplacement that have not been addressed in this study, but could be future studies.

Further study could be on the mafic enclaves and their origin in the pluton. A study done by Ayrton (1988) looked at enclaves deformed into ellipsoids, similar to those in the Donner Summit pluton, to determine whether there was compositional zoning in the pluton. Other studies also address the question of compositional zoning as illustrated by mafic enclaves (Bateman et al., 1963; Swanson, 1986) in the Sierra Nevada batholith. Vernon (1984) noted igneous textures of enclaves and the geometry of their contact with the granitoid. His results suggested that there had been a juxtaposition of two liquids containing a variable amount of crystals. Studies comparable to these may help to determine models of magma-mixing applicable to the Donner Summit pluton. The measurement of the axes of the apparently flattened mafic enclaves could also help determine local principal strain directions and paleostress conditions in the pluton.

Although composite dikes having both "felsic-mafic" and "mafic-felsic" sequences are found in the Donner Summit pluton, these interesting structures were not studied further in this thesis. By determining the timing sequence of the intrusion of the different magma compositions in the composite dikes, it may shed some light on suggestions of multiple episodes of magma injection into fractures in the Donner Summit pluton.

Fractures have hydraulically-fractured the rock ahead of the crack tip in the Donner Summit pluton. But even as this work has been completed, many other studies have been produced regarding the formation and emplacement of fractures and faults in rock masses. Rubin (1990) has looked at the stress concentration in the process zone and shown dike propagation limitations with regard to the rock mass and the surface of the Earth. In Rubin's 1993 paper he suggests that the fracture as it propagates behaves as a drained fracture and partial melt may seep fill in the fracture behind the tip. There are numerous studies that will help to better interpret the mechanics of fractures and the deformation along the fracture planes in the Donner Summit pluton.

APPENDIX A

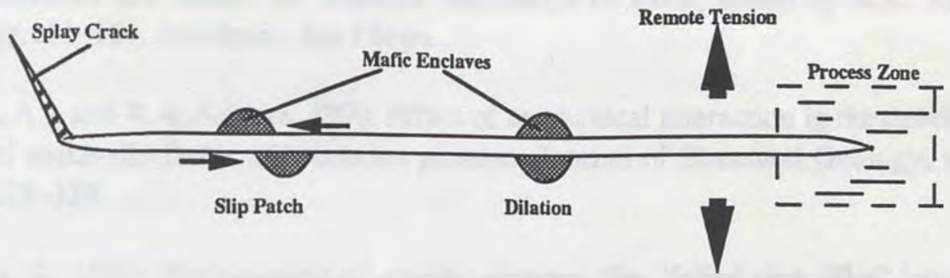
ROAD LOG

Total miles	*Distance between stops*	
0.0	0.0	**Reno Hilton.**
		Exit on the east side with light at Mill Street, heading west;
take		entrance ramp to 395 North straight.
1.2	1.2	Turn right onto Exit 68. Turn-off for I-80 West.
3.1	1.9	Exit 13: University of Nevada, Reno at Virginia Street exit.
16.9	5.0	California State line.
23–23.7	0.7	Right side: Lahar flows in the Truckee River Canyon.
26.5	2.8	Right side: Red soil from cinder cone eruption.
30–30.2	3.5	Left side: Columnar joints in the crater of a volcanic cone.
31.1	0.9	Truck Station. Off to the left is Northstar Ski Resort.
34.1	3.0	Exit for North Shore Lake Tahoe (US 89).
36.2	2.1	Exit for South Shore Lake Tahoe (US 89); Squaw Valley & Alpine Meadows Ski Resorts.
37.5	1.3	Stop! Agricultural Inspection Checkpoint.
40.3	2.8	Right side: Vista area of Donner Lake; Donner Summit pluton is located on the far west side of the lake.
44.4	4.1	Right side: Donner Summit Visitor's Center.
45	0.6	Pacific Crest Trailhead on the right side; Boreal Ski Resort on the left side.
50.5	5.5	Turn right!

		Kingvale Exit. Turn right at stop sign at the end of the exit ramp. Take an immediate left onto Donner Pass Road. Go past Troy Road on the left side
52.1	1.6	**KINGVALE SITE** Turn left! South Yuba Road. Kingvale outcrop is on the left, adjacent to the South Yuba River. Turn Left! Back onto Donner Pass Road.
52.3	0.2	Hibbard's favorite outcrop.
53.9	1.6	Continue along Donner Pass Road, underneath I-80.
54.5	0.6	**BIG BEND/RAINBOW ROAD SITE** Stop! Rainbow Lodge. Outcrop is across from Rainbow Lodge. Turn right! Back onto Donner Pass Road.
55.1	0.6	Turn Right! Entrance to I-80 East.
61.0	5.9	Turn right! Soda Springs Exit. Take a left at stop sign at the end of the exit ramp (Donner Pass Road).
61.8	0.8	Right side: Soda Springs & Royal Gorge Ski Resorts.
64.2	1.4	Right side: Sugarbowl Ski Resort.
64.8	0.6	Left side: Donner Ski Ranch Resort. Start looking to the right side for outcrops with large enclave concentrations and felsic dikes!
65.5	0.7	**OBSERVATION POINT SITE** Stop! Donner Summit observation point. Below brick wall is an outstanding exposure for magma-mixing discussion and dike kinematics.
66.0	0.5	Stop! (Optional) Mafic, felsic, and sandwich dikes, plus some enclave-dike interaction and displacement.

68.3	2.3	Approximate eastern edge of the Donner Summit pluton.
72.0	3.7	Stop sign! Turn Left! Entrance to I-80 East to return to Reno.
106	26.9	Exit 13 for University of Nevada, Reno.
107.2	1.2	Turn right! Exit for US 395 South toward Carson City.
108.4	1.2	Turn right! Exit for Mill Street and the Reno Hilton.

APPENDIX B



Process Zone = A region of inelastice deformation at a fracture tip. In this region microfractures grow and propagate. These dike-parallel fractures decrease in abundance away from the dike tip. (adapted from Delaney et al., 1986).

Mafic Enclaves = A fine-grained, mafic-rich, rounded dioritic inclusion found in the Donner Summit pluton host rock. These inclusions predate the intrusion and deformation of the dikes, and serve as convenient markers for dike displacements.

Splay Crack = This crack will form at the fracture tip if the slip patch stress extends to the fracture tip. The splay crack shown above is to illustrate in what area a splay crack would form at the dike tip.

Dilation = Dilation of a dike with a mafic enclave used as a passive marker is commonly seen in the Donner Summit pluton. The only sense of movement apparent along the dike in this region is the pure dilation of the dike caused by remote tension.

Slip Patch = This is an area along a dike where localized lateral displacement has occurred. A mafic enclave is shown displaced in the above diagram, but the slip is not consistent along the entire length of the dike.

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